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Using Combined Snowpack and Rainfall Interception Components to Assess Hydrologic Recovery of a Timber-Harvested Site: Working Toward an Operational Method

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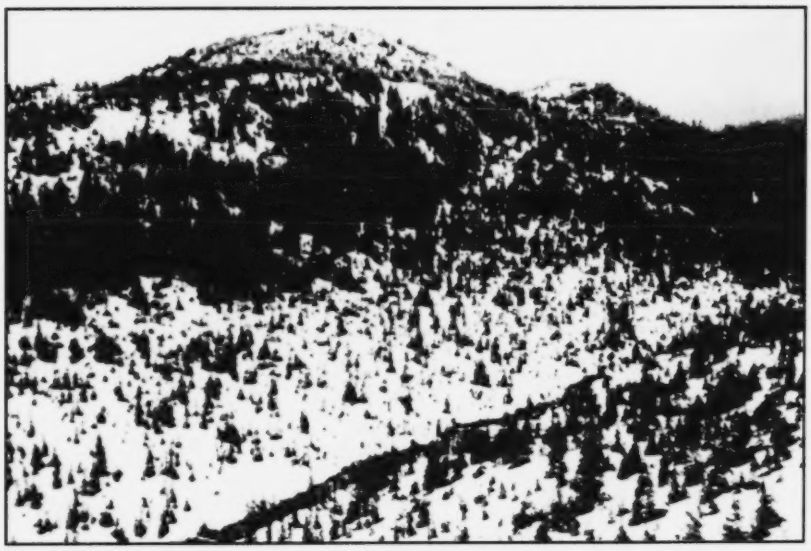

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture Systems ~ Wildlife

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Cover photo: North aspect slope in the Gray Creek study area.

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ABSTRACT

This report describes the second of several steps being taken toward developing a science-based, comprehensive, integrated approach for assessing full hydrologic recovery of timber-harvested sites in coastal British Columbia watersheds. It builds on an earlier report, British Columbia Ministry of Forests' *Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region*, that describes a regional approach for applying the snowmelt recovery method.

The results of a rainfall interception study conducted on the mainland coast of British Columbia are described and then combined with results from other rainfall interception studies to form rainfall interception recovery curves. These curves are combined with a previously reported snowmelt recovery curve to form a unified method of determining hydrologic recovery due to snowmelt, rain-on-snow, and rainfall.

KEYWORDS

forestry, forest harvesting, forest management, hydrology, hydrologic recovery, peak flow, rainfall interception, clearcuts, snowpack, snowpack recovery, snowmelt, watershed, watershed assessment, Vancouver Forest Region, British Columbia

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INTRODUCTION

Full hydrologic recovery of a site to pre-timber-harvesting conditions is based on three components: snowpack recovery, rainfall interception recovery and evapotranspiration recovery. Snowpack recovery has been well documented for coastal sites in British Columbia (Hudson 2000a, b), based on changes in snow interception and melt rate that occur when forests are harvested and subsequently regenerate. The evapotranspiration component is relatively minor as it applies primarily to summer low flows. Thus, a practical method of assessing hydrologic recovery should consist of both snowpack and rainfall recovery components. At lower elevations (<300 m) the rainfall component is dominant, and in the 300–800-m elevation band, also known as the rain-on-snow (ROS) zone, runoff is generated by both rainfall and snowmelt in proportions that vary according to storm size (Hudson 2000b).

Previous studies of rainfall interception were conducted by Spittlehouse and Black (1981), and by Giles (1983). In the former, study areas were set up near Courtenay (**Figure 1**). Giles' study plots were laid out on a hillside transect at Cowichan Lake, from valley bottom to ridge top, 72 years after fire destroyed the original forest. In these studies, the interception losses were calculated over the course of one year. Spittlehouse's and Giles' data for mature forest suggest that potential interception is about 25–35%. More recently, Spittlehouse (1998) has studied rainfall interception under immature as well as mature canopies at Carnation Creek (on the west coast of Vancouver Island, near Tofino) and near Campbell River (40 km north of Courtenay), thereby providing the basis for assessing rainfall interception recovery. Hudson (2000b) has described the development and application of a method to determine snowmelt recovery.

This technical report discusses a rainfall interception study conducted at Upper Gray Creek (on the Sunshine Coast, ~40 km northwest of Vancouver). Then, the results of this and other rainfall interception studies will be combined to form rainfall interception recovery curves. These curves will be combined with the previously reported snowmelt recovery curve to form a unified method of determining hydrologic recovery due to snowmelt, rain-on-snow, and rainfall.

METHODS

Data Collection

The site of the rainfall interception study being reported here is Upper Gray Creek. This is the same site that was used to develop the snowmelt recovery curves, and has been described in detail by Hudson (2000a, b). To study snow accumulation and melt under different regenerating stands, ten snow courses were established. The current study used plots within four of those snow courses to study rainfall interception using the methods described by Spittlehouse (1998). Data were combined with Spittlehouse's data to form a rainfall interception recovery curve for lower and upper elevations.

The study area at Upper Gray Creek was progressively harvested between the late 1950s and the mid-1980s, leaving a patchy forest cover and stands of various ages (Figure 1).

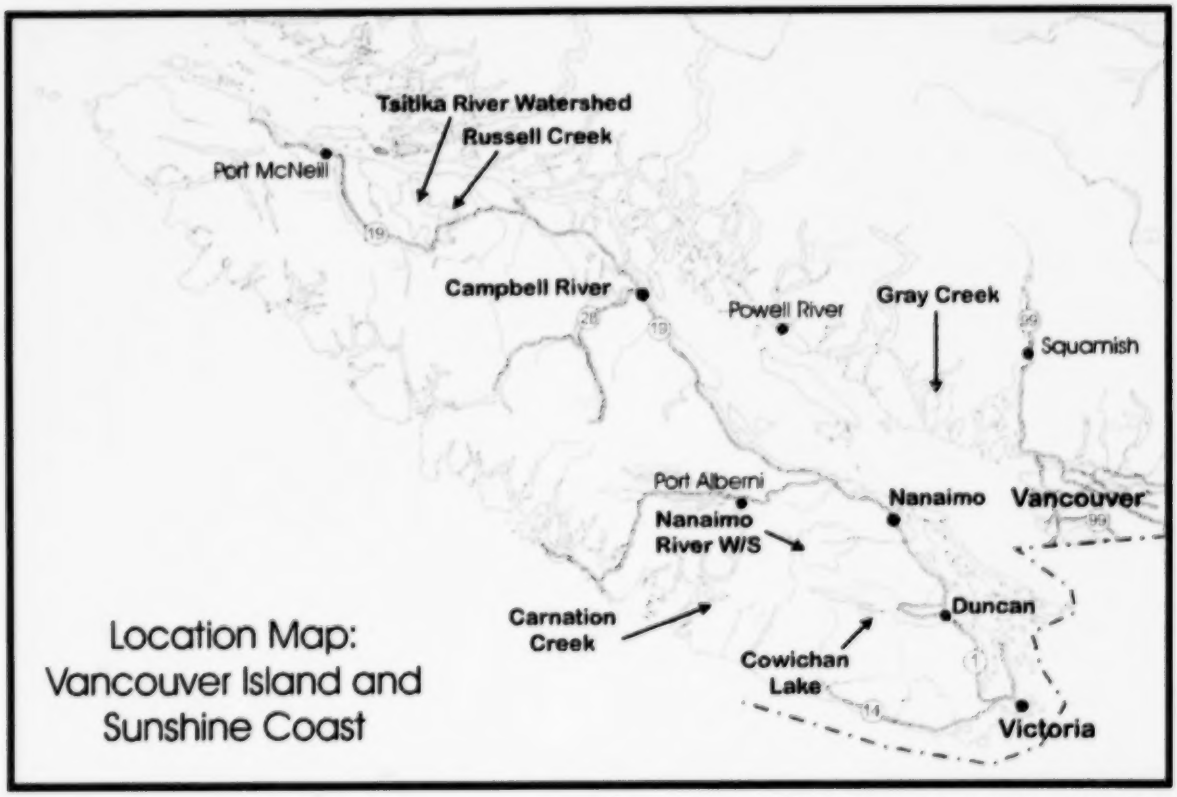
The species mix is dominated by subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) throughout the study area, with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata Donn*) at lower elevations, merging to mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) and yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach) at higher elevations. Western white pine (*Pinus monticola*) also occurs sporadically, either as individual trees or in clumps.

Rainfall interception was measured in 0.01-ha plots in which throughfall and stemflow were measured directly. One study plot was established in an old-growth stand (at Site F), and three study plots that represented regenerating stands of different ages and stand structures (at Sites C, D, and E) (**Table 1**). Rainfall and total precipitation are measured at two meteorological sites in the study area.

Following the methods described by Spittlehouse (1998), throughfall was measured with a series of troughs that were laid out under the forest canopy. They fed into a central drain system that channeled the water into a tipping bucket calibrated to tip after receiving 750 ml of water. The area of troughs at each plot was about 1.8 m^2. Stemflow was collected with a garden hose, cut in half lengthwise and cemented around a tree in a helix pattern, and measured by feeding the hose into a standard tipping bucket rain gauge. To date, rainfall interception has been measured for 26 storms between October 2000 and November 2001 (**Table 2**). Fall measurements were collected until the end of the storm on 01 December 2000, after which snow and ice conditions in the troughs and tipping buckets prevented further monitoring. Measurement resumed after the system was reactivated in May 2001.

This monitoring was intended to supplement data collected by Spittlehouse in order to determine if interception characteristics were noticeably different between high-elevation and low-elevation stands. While the trough area used to measure throughfall was comparable to that used by Spittlehouse, it was not possible to measure the catch of each trough separately. Thus the variability between troughs could not be assessed.

Also, there was only one measurement of stemflow at each site, whereas Spittlehouse collected five measurements per study plot. These facts indicate that the data presented here are potentially less precise than data presented by Spittlehouse; however, it is felt that the data are sufficiently accurate for this study.



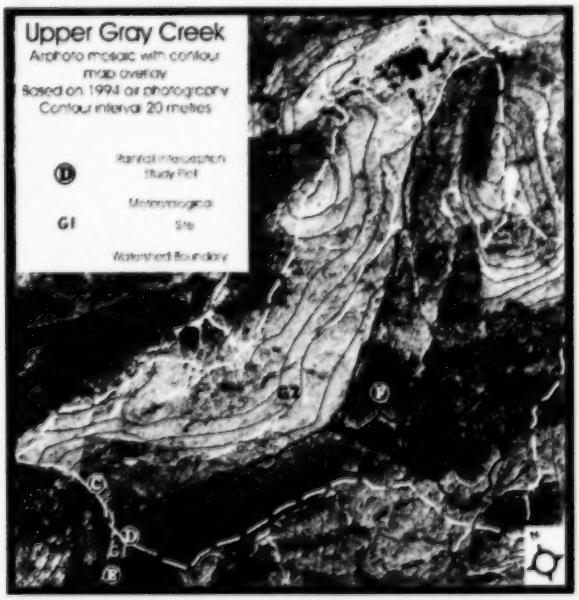


Figure 1. Above: Map of Vancouver Island and the Sunshine Coast showing locations of the study sites.
Left: An air photo mosaic of the study area at Gray Creek with a contour map overlay. The patchiness of the regeneration provided a range of stands of different ages and heights while the small area of the watershed (100 ha) helped to control the climatic variability.

Data Analysis

Throughfall was calculated by dividing the volume of water collected in the trough system by the area of the troughs, and expressed in millimetres. Stemflow was calculated for the study plot by dividing the volume of flow measured for individual trees by the area of the plot and multiplied by the number of trees in the plot. Because rainfall measurements are collected in the open, they are not affected by canopy interception. Therefore, interception loss at the forested sites for a given storm is calculated as the storm rainfall in the open, minus the total of the throughfall and stemflow for the plot. Interception loss is expressed both in terms of millimetres of rainfall intercepted by the canopy, and as a percentage of storm rainfall (Table 2b). Mathematically, the interception can be formulated as follows:

Table 1. Rainfall interception and stand variables: summary.

Data source	Canopy type	Dominant species	Stocking density (no. stems/ha)	Canopy density (%)	Stand height (m)	Annual interception (%)
Spittlehouse	Mature	Western hemlock	480	85.0	35	30.0
	Immature	Douglas-fir	1050	85.0	15	21-22
	Immature	Sitka spruce	1500	75.0	6	14.0
	Immature	Douglas-fir	1090	70.0	13	11-17
	Immature	Douglas-fir	1050	85.0	33	20-22
Gray Creek						
Site F	Old growth	Abies Mountain hemlock Yellow-cedar	700	90	32	30.1
Site E	Immature	Abies Western hemlock	500	88	18	29.4
Site D	Immature	Abies Western hemlock	2100	66	8.8	19.5
Site C	Immature	Abies Western hemlock Yellow-cedar	2180	47	5.5	9.0

$$I = PP - T - S \quad (1)$$

where,

I, PP, T, and S are interception, rainfall, throughfall, and stemflow, all in millimetres.

Expressed as a percentage,

$$I(\%) = \frac{PP - T - S}{PP} * 100 \quad (2)$$

According to the concept of hydrologic recovery, a harvested site is considered fully recovered when its potential influence on runoff becomes indistinguishable from that of a mature reference stand that represents the hydrologic characteristics of the stand prior to harvesting. To calculate rainfall interception recovery for an immature stand, the interception loss of that stand is divided by the interception loss of the reference stand:

$$R_{Stand} = \frac{I_{Stand}}{I_{Ref}} * 100 \quad (3)$$

where,

R_{Stand} and I_{Stand} are the recovery and interception ratios of the stand in question (expressed as percentages), and

I_{Ref} is the interception for the reference stand.

Hence, recovery can be calculated over any time period, from an individual storm to a season or a year.

For each of 26 storms measured between October 2000 and November 2001, the total rainfall at each meteorological site—along with the total throughfall and stemflow at Sites C, D, E, and F—were calculated (**Table 2a**). These data were then used to calculate the interception loss during each storm at each one of the measurement sites (**Table 2b**). The recovery factor was not calculated for Site F because this site is in old growth, which by definition represents 100% recovery. For each of Sites C, D, and E, the recovery factor was calculated using Equation 3. The data are grouped into three distinct time periods:

1. Fall of 2000, including 6 storms
2. June 2001, 3 storms, and
3. Fall of 2001, represented by 17 storms.

Rainfall interception was calculated on a storm-by-storm basis. Values for rainfall interception recovery were calculated for each storm by dividing the interception loss for a second-growth stand by the interception loss of the old-growth stand for that particular storm. The recovery values for immature stands were calculated in two ways: as an average of the storm recovery values for the period during which each plot was operating (Table 2b), and as an overall recovery ratio for all storms lumped together (**Table 2c**).

Method 1 can be formulated as:

$$R_{X1} = \frac{\sum_{i=1}^{n} R_i}{n} \quad (4)$$

Table 2a. Storm rainfall, throughfall, and stemflow (mm) at Gray Creek.

Storm date	Rainfall		Site F [a]		Site E [b]		Site D		Site C	
	Gray1 (mm)	Gray2 (mm)	Through-fall (mm)	Stem-flow (mm)	Through-fall (mm)	Stem-flow (mm)	Through-fall (mm)	Stem-flow (mm)	Through-fall (mm)	Stem-flow (mm)
18-Oct-00	60.2	66.0	48.1	0.248	35.3	0.642	53.0	1.064	NA	NA
21-Oct-00	79.6	84.0	57.0	0.610	44.8	1.515	65.7	2.669	NA	NA
29-Oct-00	60.2	68.0	59.1	0.342	36.5	0.642	54.5	1.064	NA	NA
31-Oct-00	6.5	7.0	3.3	0.000	3.3	0.002	4.6	0.000	NA	NA
04-Nov-00	17.2	18.0	12.3	0.104	11.9	0.020	13.8	0.016	NA	NA
01-Dec-00	74.2	85.0	18.5	0.144	12.9	0.714	21.9	1.195	NA	NA
01-Jun-01	21.4	24.0	2.7	0.210	6.0	0.104	15.0	0.179	NA	NA
10-Jun-01	7.0	7.0	0.0	0.057	2.3	0.003	5.0	0.000	NA	NA
11-Jun-01	9.3	9.0	0.5	0.086	2.5	0.050	5.5	0.08	NA	NA
28-Sep-01	10.4	11.0	9.1	0.005	7.4	0.008	5.2	0.005	NA	NA
29-Sep-01	5.0	5.0	2.3	0.005	3.0	0.002	5.2	0.000	NA	NA
07-Oct-01	10.4	11.0	6.9	0.005	6.5	0.008	1.7	0.005	8.5	0.007
09-Oct-01	21.1	23.0	18.7	0.029	17.4	0.047	13.9	0.047	19.6	0.092
21-Oct-01	14.9	16.0	11.9	0.014	13.0	0.020	Plugged	0.015	13.3	0.029
22-Oct-01	25.2	27.0	21.0	0.076	19.0	0.044	Plugged	0.085	22.1	0.080
24-Oct-01	5.9	6.0	2.7	0.010	5.6	0.003	Plugged	0.001	Plugged	0.001
25-Oct-01	19.3	21.0	15.5	0.043	16.0	0.038	Plugged	0.035	Plugged	
26-Oct-01	13.1	14.0	10.5	0.052	11.8	0.015	Plugged	0.010	Plugged	
30-Oct-01	14.9	16.0	8.7	0.019	8.8	0.020	9.27	0.015	Plugged	
01-Nov-01	13.1	14.0	8.7	0.029	9.8	0.015	2.32	0.010	12.3	0.019
04-Nov-01	16.7	18.0	13.3	0.029	15.3	0.055	13.04	0.080	15.4	0.157
11-Nov-01	39.1	43.0	33.4	0.071	26.9	0.193	31.80	0.245	32.8	0.481
13-Nov-01	55.2	61.0	52.6	0.405	47.4	0.589	46.80	0.915	49.1	1.793
14-Nov-01	48.9	54.0	43.4	0.733	29.7	0.431	41.39	0.650	44.5	1.273
19-Nov-01	74.9	83.0	68.6	0.709	59.0	1.409	67.08	2.363	65.8	4.632
20-Nov-01	33.7	37.0	30.6	0.276	34.8	0.147	29.90	0.186	27.7	0.364

[a] Site F (old growth) is referenced to rainfall at site Gray 2 (G2) (Figure 1).
[b] Site E is referenced to Gray1.

where,

R_{X1} is the average recovery ratio of plot X averaged over n storms.

Method 2 can be formulated as:

$$R_{X2} = \left\{ \frac{\sum I_X}{\sum PP} \Big/ \frac{\sum I_{Ref}}{\sum PP} \right\} * 100 \qquad (5)$$

In this case, the time periods of PP and I_{Ref} must match the period during which the immature plot was operating. For example, Plot C operated only in the fall of 2001, and therefore its recovery ratio is calculated relative to old-growth interception for that same period (Table 2c). Using Method 1, the calculated mean recovery is independent of the time period over which the plot is operated but may be biased toward smaller storms. Using Method 2 probably gives more weight to the larger storms, but may be partly dependent on annual climatic trends, and interception conditions as noted above. An attempt was made to adjust for these differences by adjusting the interception ratios for Plots C and D by the ratios of interception losses at Plot E for the specific period relative to that for the whole period. There is a 6% difference between the two methods in the Gray Creek data. For the remaining analysis, the recovery ratios calculated by Method 2 are used, because the data reported for the Carnation Creek sites were calculated from annual storm-based interception data reported by Spittlehouse (1998).

Finally, to develop a recovery curve, the calculated re-

Table 2b. Interception losses calculated for storms in Table 2a, and average values.

Storm date	Site F		Site E			Site D			Site C		
	Interception loss		Interception loss		R	Interception loss		R	Interception loss		R
	(mm)	(%)	(mm)	(%)	(%)	(mm)	(%)	(%)	(mm)	(%)	(%)
18-Oct-00	17.7	26.7	24.3	40.3	100.7	6.2	10.2	38.2	NA	NA	NA
21-Oct-00	26.4	31.4	24.3	30.5	97.2	11.2	14.1	44.9	NA	NA	NA
29-Oct-00	8.6	12.6	23.1	38.3	95.7	4.6	7.7	60.9	NA	NA	NA
31-Oct-00	3.7	53.4	3.2	49.2	92.1	1.8	28.6	53.5	NA	NA	NA
04-Nov-00	5.5	30.8	5.2	30.5	98.9	3.4	19.6	63.4	NA	NA	NA
01-Dec-00	45.0	76.2	36.7	66.1	Freezing	32.4	58.4	Freezing	NA	NA	NA
01-Jun-01	21.0	87.7	15.4	71.6	81.7	8.8	36.6	41.7	NA	NA	NA
10-Jun-01	6.9	99.2	4.7	66.8	67.3	2.0	28.6	28.8	NA	NA	NA
11-Jun-01	8.5	94.0	6.7	72.1	76.7	3.7	39.9	42.5	NA	NA	NA
28-Sep-01	1.8	**29.6**	2.9	28.3	95.7	2.6	**15.3**	51.6	NA	NA	NA
29-Sep-01	2.7	54.1	2.0	39.6	NA	-0.2	NA	NA	NA	NA	NA
07-Oct-01	4.1	39.8	3.9	37.3	93.6	2.6	**26.0**	65.3	1.9	18.3	45.9
09-Oct-01	4.2	18.4	3.7	17.4	94.7	5.6	26.4	67.7	1.4	6.7	36.7
21-Oct-01	4.1	**24.9**	1.8	12.4	**67.8**	Plugged	Plugged	NA	1.6	10.6	42.5
22-Oct-01	5.9	**29.3**	6.2	24.4	83.2	Plugged	Plugged	NA	3.1	12.1	41.4
24-Oct-01	3.2	32.1	0.3	13.4	NA	Plugged	Plugged	NA	Plugged	Plugged	Plugged
25-Oct-01	5.4	**27.3**	3.3	**13.9**	50.9	Plugged	Plugged	NA	Plugged	Plugged	Plugged
26-Oct-01	3.4	24.5	Combined with previous			Plugged	Plugged	NA	Plugged	Plugged	Plugged
30-Oct-01	7.3	45.6	6.0	40.5	88.9	5.6	**37.5**	82.3	Plugged	Plugged	Plugged
01-Nov-01	5.3	37.7	3.3	25.3	67.0	10.7	NA	NA	0.8	13.9	36.7
04-Nov-01	4.7	26.2	1.3	**23.7**	90.6	3.5	21.3	81.2	1.1	14.5	55.3
11-Nov-01	9.5	22.2	11.9	30.6	137.6	7.0	18.0	NA	5.8	11.9	53.6
13-Nov-01	8.0	**17.1**	7.2	13.1	**138.4**	7.5	13.6	79.2	4.4	3.6	21.2
14-Nov-01	9.8	20.1	18.8	38.4	Combined	6.9	14.1	70.1	3.2	6.5	32.3
19-Nov-01	13.7	18.3	14.5	19.4	106.1	5.5	7.3	40.0	4.5	6.0	32.8
20-Nov-01	6.1	18.1	2.0	5.5		3.6	10.7	59.2	5.6	15.2	84.0
Averages (Method 1)					91			57			44

Table 2c. Calculation of mean rainfall recovery using Method 2: summary.

Reference	Old growth		Site E			Site D			Site C			RAIN
	Interception loss		Interception loss		R	Interception loss		R	Interception loss		R	
	(mm)	(%)	(mm)	(%)	(%)	(mm)	(%)	(%)	(mm)	(%)	(%)	(mm)
Ref to Site E	242.5	30.6	232.7	29.4	96.0		17.9	58.6		13.1	43.0	792.7
Ref to Site D	220.5	31.0	221.1	31.1	100.3	135.0	19.0	61.2		13.9	41.5	711.5
Ref to Site C	75.4	20.4	74.6	20.2	98.9	52.9	12.3	60.4	33.4	9.0	44.3	370.1
Adjusted means		27.3		26.9	98.4		16.4	60.1		12.0	42.9	

covery factors are plotted against stand structure variables (i.e., stand height or canopy density) and a curve is fitted to the data points. A Chapman-Richards curve described by Sit and Poulin-Costello (1994) was found to fit the data well; this is an asymptotic, exponential function of the same type as that which forms the snowmelt recovery curve described by Hudson (2000a, b).

RESULTS

Data Treatment

The Nature of Rainfall Interception Data

The storms for which rainfall interception was measured ranged in size from 5 to 85 mm of rain. There was a relationship between storm size and interception loss; although not well defined, the interception loss expressed as a percentage declined with increasing storm volume at each sampling plot. Interception loss was also much higher for summer storms than for fall and winter storms (**Figure 2**). Although only three summer storms were measured, this was substantiated by Spittlehouse (1998), who found the same seasonal trend. Superimposed on this relationship, Figure 2 also shows that interception loss at the old-growth and advanced second-growth sites (Sites F and E) is greater than that at Sites C and D.

Stemflow is affected primarily by the development of tree bark, such that it is more significant in younger stands, presumably because there is less bark to absorb water on young trees than on mature trees. There is a relationship between stemflow and storm rainfall that is exponential for small storms, and which becomes linear for storms >40 mm (**Figure 3**). The relationship is well defined for immature/second-growth trees, and less well defined for old-growth trees. Stemflow is also higher for younger trees at the stand level. This is partly due to bark development, but also partly due to the higher stocking density of younger stands (Table 1). The maximum stemflow that was measured was 4.6 mm at Site C, during the 19 November 2001 storm. This represents 5.8% of the storm rainfall. In all other cases the stemflow was <5% of the storm rainfall. Expressed as a percentage of storm rainfall, the stemflow in the immature stands can be represented by a power function (for example, at Site D), while at the old-growth plot, stemflow was usually <1%

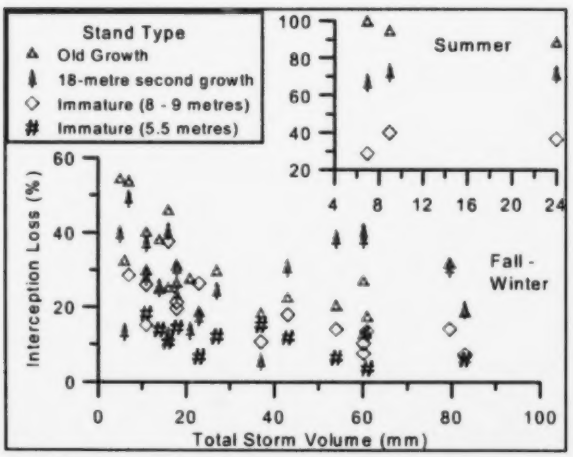


Figure 2. Relationships between interception loss and storm size (mm) for mature and immature forest stands at upper Gray Creek.

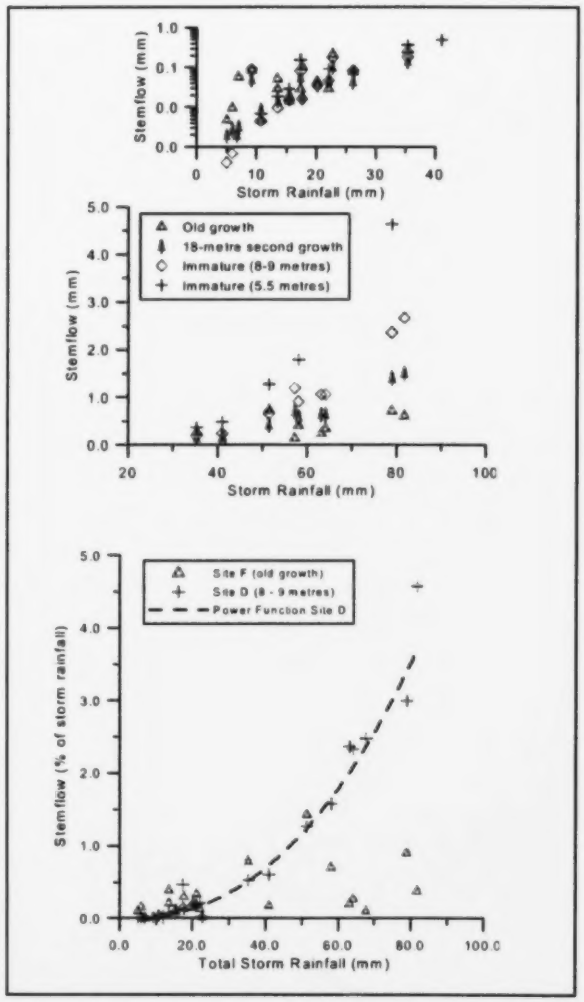


Figure 3. Relationships between stemflow and storm rainfall for mature and immature forest stands at upper Gray Creek. Top and middle: mm of stemflow vs. mm of rainfall. Bottom: stemflow as a percentage of storm rainfall.

of storm rainfall (Figure 3, bottom). The one storm when the stemflow exceeded 1% was the most intense storm measured, with rainfall intensities reaching 10 mm/h.

As noted above, the interception recovery data are presented and used as averages over time. The error in measuring interception tends to be high for individual storms, and that error is reduced by averaging interception losses over many storms. Hudson (2000b) observed the same thing when discussing the snowpack recovery results. The error is probably due in large part to the inherent variability of naturally occurring forest stands and the meteorological phenomena that influence the effect of the stand on hydrology of the site. To show this visually, the recovery data given in Table 2 for individual storms were plotted against stand height along with statistical properties of the distribution of those storm recoveries (**Figure 4**). The recovery at each stand, calculated for individual storms, forms a probability distribution that is close to a normal distribution. Note that the variability increases as the stand height increases. The 95% confidence limits of the mean of each distribution quantify the variability under each stand. Because the precision in measuring rainfall and interception does not change from site to site, the increase must be attributed to the stand and not to measurement error. This suggests that increasing stand complexity is a major contributor to the error in determining hydrologic recovery. For example, the "recovery" calculated for the old-growth stand for each storm was calculated as the ratio of the storm interception to the overall mean interception loss of all storms, thus the old-growth stand is 100% ± 17.1% recovered, while the 5.5-m immature stand has a mean recovery ratio of 39.8% ± 7.4%. If the half interval is plotted against stand height a linear relationship is formed that has an X-intercept of 5% (Figure 4, bottom). Thus measurement error is 5%, and the variability due to the stand accounts for up to ±12% under old growth.

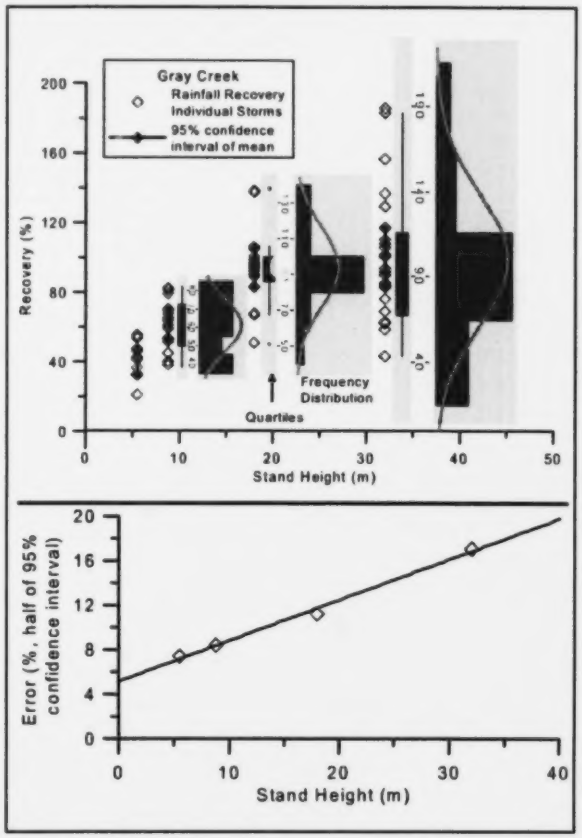


Figure 4. Statistical distribution of recovery data for individual storms at Gray Creek. Bottom: The error (half of the 5% confidence interval) as a function of stand height forms a linear relationship suggesting that measurement error is ±5%.

Reference Stands for Determining Recovery

Rainfall interception depends on stand characteristics and rainfall regime. The amount of water that a tree can hold depends on the size and shape of its crown, the thickness of its bark, the presence of moss and lichen in the canopy, etc. (Spittlehouse 1998). Therefore the interception expressed as a percentage of rainfall depends on the species, size, and age of the trees, and on the rainfall regime.

Clearly the Vancouver Island Mountain Range divides the Island into east and west coast regimes for snow (Hudson 2000 b) and rainfall. For example, Environment Canada (2003) reports that the long-term mean annual rainfall at Tofino is almost three times that at the Nanaimo airport. In addition to this, annual rainfall volumes up to three times that of the Tofino site have been measured at individual sites on the west side of the Island in the Port Alberni area. Because individual trees have a finite capacity to hold water, a given stand will intercept a larger fraction of rainfall in an east coast regime compared to a west coast regime, because the frequency and magnitude of storms in an east coast regime is lower than that in a west coast regime.

A reference site to determine rainfall interception recovery for an immature stand should be of a similar species mix and from the same rainfall regime. Gray Creek is a Snow Accumulation Zone 4 watershed, which is equivalent to an east coast (Vancouver Island) regime; at the study site, the species mix is similar at each plot. Thus the Gray Creek site is well controlled. Among the Vancouver Island stands there is a mixture of species and regimes. However, there is only one old-growth stand, composed of western hemlock, and the immature stands are composed of Douglas-fir and Sitka spruce. There is no mature Douglas-fir stand in which rainfall interception has

Table 3. Interception under mature Douglas-fir, 1951-53: Nanaimo River, and other sites.

Data source	Stand height (m)	Site index	Annual		Interception loss	
			Precipitation (mm)	Interception (%)	Fall/ winter I_w (%)	Spring/ summer I_s (%)
McMinn (1957)	27.3	19.8	1733.0	24.3	15.7	37.0
	32.9	26.2	1437.5	25.0	18.1	38.5
	45.7	39.6	1426.0	28.0	15.4	44.8
	52.4	42.7	1380.0	32.5	18.2	49.7
	62.9	51.8	1347.5	35.0	24.5	50.7
	73.7	61.0	1353.3	43.5	37.0	53.0
Mean annual precip. (1951-53)			1446.2			
Nanaimo River (1952)		2070.1	2070.0			
Cowichan Lake (1952)			2235.0			
Rothacher (1963)	60.0		2131.0		13.7	24.0
Adjusted to Nanaimo R. regime					21.2	37.1
Gray Creek [a]	32.0		1041.0 [b]	27.7	23.8	58.0
Adjusted to Nanaimo R. regime				19.9	14.0	38.8
Carnation Creek [c]	35.0		3473.0	30.0	24.3	38.5
Adjusted to Nanaimo R. regime					59.0	92.5

[a] Old-gowth subalpine fir.
[b] Rainfall only reported.
[c] Mature western hemlock.

been measured to act as a control for the immature Douglas-fir stands. It is therefore necessary to refer to the literature to develop a suitable reference for those stands. Simulated reference stands were developed from rainfall interception and precipitation data reported by McMinn (1957) and Rothacher (1963) for mature Douglas-fir, and adjusted using rainfall data from Tofino, Nanaimo, and Campbell River airports (Environment Canada 2003).

McMinn (1957) measured rainfall interception in old-growth Douglas-fir stands from 1951 to 1953 and reported interception from 37 to 53% in summer and 24 to 43% annually in the Nanaimo River area for stands from 27 m to 74 m tall. Precipitation data from various sites around the Nanaimo River area, including Cowichan Lake, were also reported for 1952 (**Table 3**). McMinn reported seasonal rainfall and interception, but for different seasonal periods than those used by Spittlehouse (2001). Therefore adjustments were made to the seasonal data and a method developed to calculate spring/summer and fall/winter interception from summary data (Appendix B). This resulted in a model of seasonal and annual interception for old-growth Douglas-fir to act as reference stands appropriate to the immature Douglas-fir at Cowichan Lake and Campbell River (Table 3). The results provide good predictive relationships between seasonal interception losses and stand height (**Figure 5**). For winter interception the relationship is linear for stands <46 m tall and then becomes exponential up to the maximum stand height of 74 m. This probably represents the period of time over which a "mature" Douglas-fir stand ages toward "old growth". This process might take hundreds of years. The relationship for summer interception is logarithmic. The difference between the two relationships suggests that this same aging process may be less important for summer interception than for winter interception.

A comparison between measured old growth interception at three different sites (Oregon, and Carnation and Gray Creeks) and the McMinn relationships (Figure 5) shed some light on the relative importance of rainfall regime and stand structure in governing interception. Rothacher (1963) obtained interception values of 24% in summer and 13.7% in winter in Oregon for Douglas-fir up to 60 m tall (Table 3). Spittlehouse reports mean annual interception of 30% in old-growth hemlock at Carnation Creek (west coast Vancouver Island regime). A fall/winter value was calculated at 24%. At the Gray Creek site, the overall average rainfall interception at the old-growth stand (predominantly Abies lasiocarpa and Tsuga mertensiana) was 28%, and for winter interception it was 23.8%. Interception data from all three sites were adjusted to the Nanaimo River regime using the precipitation ratio; the adjusted values from Rothacher's Oregon Douglas-fir stand and from Gray Creek fall on the same curve as the Nanaimo River for winter interception, but

not for summer interception. The Carnation Creek hemlock interception data does not agree for either winter or summer interception. This suggests that winter interception is less sensitive to differences in stand structure than summer interception. The interception vs. stand height relationship for winter interception based on McMinn's data is reliable for a range of regimes and can be used to assess rainfall interception recovery for the Vancouver Island Douglas-fir stands. A more cautious approach may be warranted for assessing summer interception recovery for those same stands; however, the relationship allows recovery curves to be developed for different reference heights, thereby introducing more flexibility into the calculation of hydrologic recovery.

Selection of a "Stand Descriptor"

The primary dilemma in deriving an operational method such as this is: How can we make the method relatively simple to use without losing the inherent complexity of the processes involved? Given that forest stand dynamics are sufficiently complex that one stand descriptor alone cannot adequately represent the recovery process, this suggests that a composite stand descriptor must be developed. The primary factor that controls interception is the size of the tree crowns, which at the stand level can be described by the canopy depth and the canopy density. For regenerating trees in the size range in which recovery occurs, the canopy depth is essentially the same as the tree height.

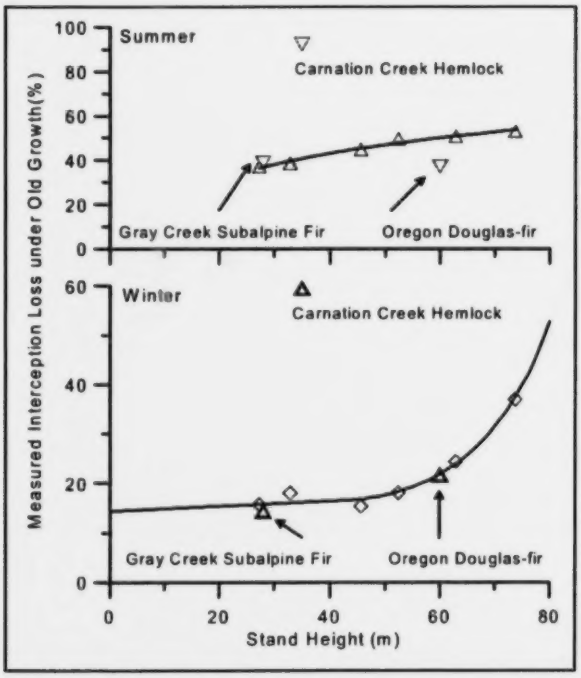


Figure 5. Summary of measured interception loss under old growth Douglas-fir stands. The curves represent an interception model based on McMinn's Nanaimo River stands, plus data from other sites adjusted to Nanaimo River rainfall regime for comparison. Gray Creek and Oregon stands agree with the model for winter interception.

While investigating snowmelt recovery, it was determined that stand height (the average height of the dominant and co-dominant trees) was the primary stand descriptor governing snow recovery in coastal stands (Hudson 2000a). Canopy density did not provide any additional information when introduced into the analysis. Theoretically, it was expected that in the case of rainfall interception, canopy density might be the primary variable responsible for the recovery process. Other variables to be considered include species, site index, and some measure of the age of the stand, because older trees develop thicker bark that is capable of absorbing a significant quantity of water.[1]

As a "first approximation"—pending further development as described later in the report—all preliminary recovery data from different sources were plotted against stand height and canopy density (**Figure 6**). The data set includes data collected at Gray Creek (as described earlier in this report), as well as the summarized snowmelt and snow accumulation recovery data (Hudson 2000b) and data reported by Spittlehouse (1998, 2001). At this initial stage the data summarized as annual means were used. The data form logical groups when stand height is used as the descriptor (Figure 6, top), and the data suggest that there may be more than one curve. When plotted against canopy density (Figure 6, bottom) there also appears to be more than one curve, but the data that define those curves do not represent any logical groupings. Thus if canopy density were used as the descriptor, it would not be possible to separate the effects of other variables such as species, rainfall regime, site elevation, etc. Therefore it is reasonable to proceed with stand height as the primary descriptor, while trying to work in the additional variability that could be explained by canopy density. When the data representing average recovery of peak snow accumulation (Hudson 2000b) are also included, they appear to conform to the same relationship as when stand height is used as a predictor. Because rainfall and snow accumulation recovery are both interception processes, it makes some physical sense to combine them into one relationship. In this case, it helps to define the lower end of the recovery curve.

On close examination of Figure 6 (top), there are some apparent anomalies that might arise from the variability in

[1] D. Spittlehouse, Research Climatologist, Research Section, BC Ministry of Forests, Victoria, BC; personal communication, 2003.

stand height. In particular, the Cowichan Lake 1 stand (Table 1) is very dense compared to the Cowichan Lake 2 stand, and more in line with the 33-m Campbell River stand. Using stand height alone assumes that there is a relationship between stand height and canopy density that defines the size of the tree crowns. Any stand that falls outside the 95% confidence bands of that relationship has a canopy size significantly different from what the relationship suggests (i.e., it is an outlier). To compensate for those differences, stand heights were adjusted to bring the outliers within the confidence bands. To do this, a logarithmic relationship between canopy density and stand height was used. In the case of the Gray Creek sites, that relationship was composed of data derived from all snow course plots in the Gray/Chapman/Roberts Creek area (aka Mount Elphinstone/ Tetrahedron Mountain) of the Sunshine Coast (**Figure 7**, bottom). In the case of overstocked stands, outliers lie above the upper confidence band. The height is adjusted to compensate for the canopy density by sliding the data point to the right, thereby placing it either on or within the confidence bands. Similarly, if a stand is understocked in comparison to other stands in the area, then its tree height is reduced to reflect the reduced interception capacity of the stand (i.e., the point is slid to the left to the lower confidence limit). Using this same method, all rainfall plots were lumped together and the canopy heights were adjusted to compensate for deviations in interception due to their relative canopy density characteristics. In this way, adjusted stand height becomes a composite variable that represents the size of tree crowns that make up the canopy.

Using adjusted stand height as the stand descriptor, the

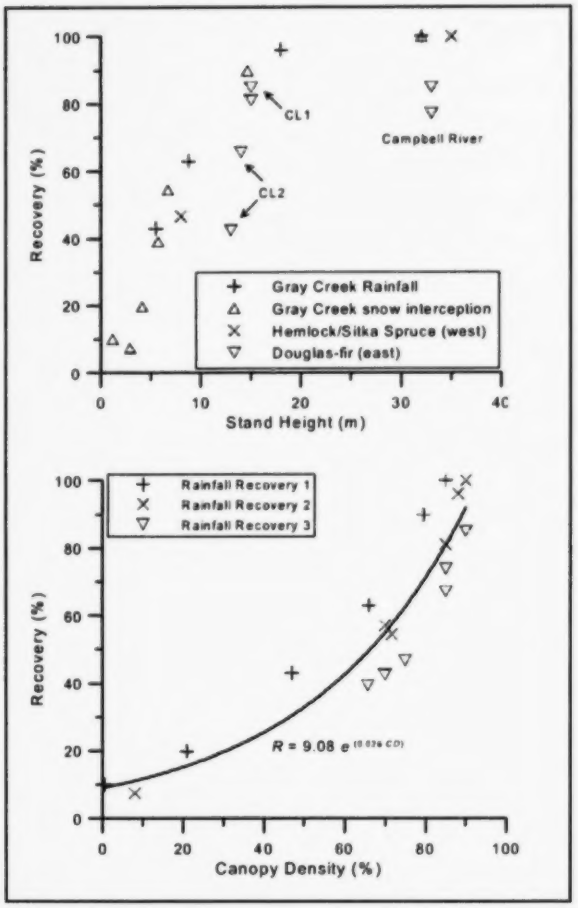


Figure 6. Rainfall interception recovery as a function of stand height (top) and canopy density (bottom). For Douglas-fir stands, CL1 and CL2 are the Cowichan Lake stands. The height curve conforms to the asymptotic function used to model snowmelt recovery, while the density curve appears to be an exponential function. While the data form logical groupings with stand height as a predictor, there is no rationale behind the different curves with canopy density as the descriptor.

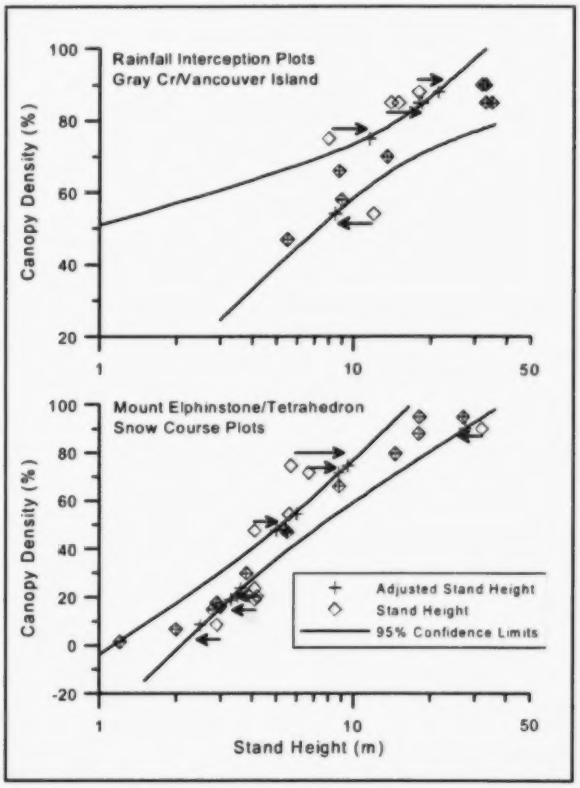


Figure 7. Adjustment of stand height to compensate for canopy density outliers.

Table 4a. Mean recovery (%) for all storms at or above a given threshold: the effects of varying the storm size threshold on rainfall recovery at Gray Creek.

	Recovery				
Stand height (m)	All storm data (%)	15-mm threshold (%)	30-mm threshold (%)	45-mm threshold (%)	60-mm threshold (%)
32.0	100.0	100.0	100.0	100.0	100.0
18.0	99.2	102.8	128.1	137.9	137.1
8.8	58.6	59.8	55.0	51.4	42.8
5.5	35.3	36.5	41.5	32.0	29.9
Storms (no.)	25	16	8	6	4

rainfall recovery data fall into two separate groups (Figure 6) in which the Gray Creek data are distinctly different from the data collected on Vancouver Island, with the exception of one plot. Snow accumulation recovery at Snow Course J at Gray Creek was similar to that of the rainfall interception recovery for Sitka spruce at Carnation Creek. That site contained a significant pine component that was not found at the other plots. This likely reflects the fact that pine tends to grow in open stands and therefore has reduced interception capability compared to other species.

Development of Recovery Curves

Influence of Storm Size on Rainfall Interception Recovery

As noted above the storm size has a very substantial effect on the components of interception. An important consideration in developing rainfall recovery criteria is the issue of storm size; that is, should recovery be based on mean annual conditions, or should it be based on seasonal conditions? This would recognize the fact that there are different concerns regarding the effects of forest harvesting on streamflow depending on the season. In the summer the main concern might be the effects of harvesting on low flows, while in the fall and winter the main concern is the potential of forestry activities to increase peak flows. By the same reasoning, there may also be a sound rationale for using only storms above a minimum size for determining hydrologic recovery, because only the larger storms contribute to channel change. Assuming that the bankfull event with a return period of 1–1.5 years is the appropriate threshold, this adds some logical basis for focusing the assessment of hydrologic recovery on the most important events.

At Gray Creek, because recovery data are available on a storm-by-storm basis, the effects of varying the storm size threshold can be investigated. To do this, recovery was determined for several thresholds by successively removing storms below the threshold, and then recalculating recovery using Method 2 for the resulting data set (**Table 4**). The result of this analysis shows that as the threshold is increased, the second-growth stand at a height of 18 m becomes progressively over-recovered compared to old growth. This effect reached a maximum at a storm threshold of 45 mm, with the recovery calculated at 139% relative to old growth (**Figure 8, top**); therefore, for large storms the advanced second-growth stands at Gray Creek is more efficient at intercepting rainfall than the old growth. This would suggest one of two things:

1. either the recovery curves should allow for these advanced second-growth stands to be over-recovered, or
2. the reference stand should not always default to old growth, but to the stand with the maximum interception capacity (**Figure 8, bottom**).

Table 4b. Comparison of recovery data calculated in three different ways.

	All storm data	45-mm threshold	
Stand height (m)	Old-growth reference (%)	Old-growth reference (%)	Second-growth reference (%)
32.0	100	100.0	100.0
18.0	99.2	137.9	100.0
8.8	58.6	51.4	45.0
5.5	35.3	32.0	25.1

When the storm threshold is increased from 0 to 45 mm the mean interception ratio of the old growth drops from around 32% to 21%, levelling off at a storm threshold of 30 mm, while under the 18-m second growth canopy interception remains steady at 29% (**Figure 9**). This suggests that the old-growth stand reaches some finite holding capacity after 30 mm of rain, at which point the effect of the gaps probably offsets the effect of any further ongoing evapotranspiration. The second growth has a more uniform canopy than the old growth that probably accounts for its greater efficiency at intercepting even the largest storms. In comparison, under the 9-m second growth the combined effect of immature trees and canopy gaps prevents it from reaching a steady state, and the interception continues to decline as the storm size threshold is increased.

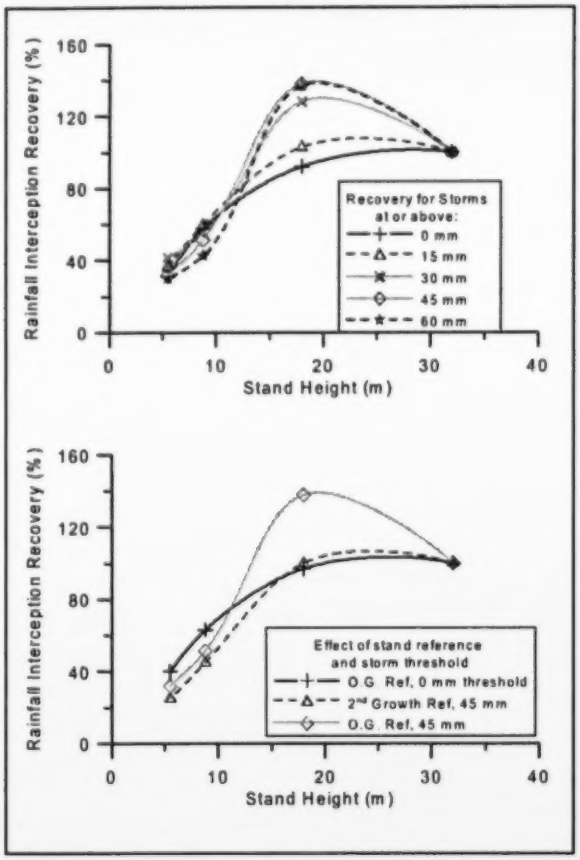


Figure 8. Top: The effects of varying the storm size threshold on recovery of immature stands.
Bottom: The effects of using second growth as a reference stand with a 45 mm storm threshold compared to other scenarios. If the old growth is the reference and all storms are included the result is the black curve. If only storms >45 mm are used then the second growth is over-recovered relative to old growth, resulting in the red curve. If the 18-m second growth is taken as the reference stand then the result is lower recovery for younger stands.

The above analysis suggests that the interception ratio of around 30% (±1%) could be taken as a "standard" interception ratio, and also supports the idea that the second-growth stand at Gray Creek can be considered a suitable reference stand for rainfall interception recovery—perhaps more so than the old growth. The suitability of a stand to act as a reference for hydrologic recovery is probably more related to the stand quality than to its actual age. The effect of altering the storm size threshold is similar to the seasonal effect noted by McMinn and Rothacher; this is partly due to the tendency of winter

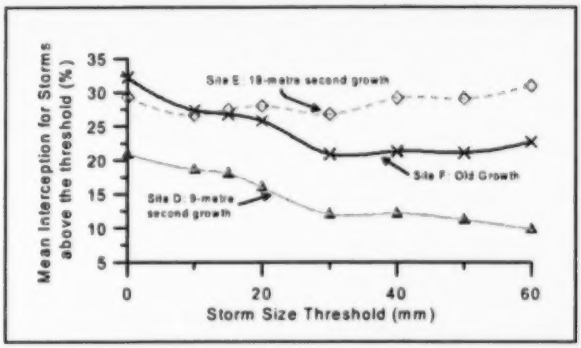


Figure 9. Mean interception as a function of storm size for three stands at Gray Creek. This helps to explain why the 18-m second growth is more efficient at intercepting rainfall than the old growth.

storms to be larger and more frequent than summer storms. At Gray Creek, the effect becomes identical above a storm threshold of 23 mm because only three summer storms were measured, and all three were below that threshold. The thresholds used to do the analysis discussed above were somewhat arbitrary; the maximum interception at Gray Creek occurred under the 18-m second-growth stand with the storm size threshold between 42 and 51 mm. Return period analysis of the annual maximum storm series from Gray creek indicates that these thresholds correspond to return intervals of 1.15 and 1.45 years respectively. This corresponds to the interval in which bankfull discharge generally occurs (Wolman and Millar 1960; Hudson 2002).

Effect of Season and the Choice of Reference Stand on Hydrologic Recovery

Only summary data are available for the Vancouver Island stands at this time, therefore the above analysis of the influence of storm size on rainfall recovery cannot yet be done for those sites. However, the Douglas-fir reference simulator provides a means to develop separate recovery curves for spring/summer and for fall/winter periods, and for different management scenarios with regard to the state of maturity that a managed forest is likely to achieve.

For immature Douglas-fir stands at Cowichan Lake and Campbell River, the following procedure was followed to generate the recovery data:

1. The measured annual and/or spring/summer interception data were used to calculate fall/winter interception data in one of two ways.

   a) If spring/summer and annual interception data were reported, then the winter interception can be calculated as

Table 5a. Rainfall interception data and associated stand data: summary.

Data source/site	Canopy type	Dominant tree species	Stocking density (no. stems/ha)	Canopy density (%)	Adjusted stand height (m)	Stand height (m)	Interception		
							Fall/ winter (%)	Spring/ summer (%)	Annual (%)
Spittlehouse									
Carnation Creek	Mature	Western hemlock	480	85	35.0	35.0	24.3	38.5	30.0
Carnation Creek	Immature	Sitka spruce	1500	75	11.5	6.0	12.5	29.0	14.0
Cowichan Lake 1 (1997)	Immature	Douglas-fir	1050	85	18.5	16.0	17.3	27.8	22.0
Cowichan Lake (1995-6)	Immature	Douglas-fir	1050	85	18.0	15.0	15.5	16.3	21.0
Cowichan Lake 2 (1997)	Immature	Douglas-fir	1090	70	13.5	14.0	15.7	19.0	17.0
Cowichan Lake 2 (1995-6)	Immature	Douglas-fir	1090	70	13.5	13.0	9.8	12.8	11.0
Campbell River (2001)	Immature	Douglas-fir	1050	85	33.0	33.0	17.8	23.3	20.0
Campbell River (2000)	Immature	Douglas-fir	1050	90	33.0	33.0	16.7	30.0	22.0
Gray Creek									
Site F	Old growth	Abies Mountain hemlock Yellow-cedar	1400	90	32.0	32.0	23.8	55.7	27.7
Site E	Immature	Abies Western hemlock	500	88	20.5	18.0	24.9	43.2	27.5
Site D	Immature	Abies Western hemlock	2100	66	8.8	8.8	14.8	23.3	16.3
Site C	Immature	Abies Western hemlock Yellow-cedar	2180	47	5.5	5.5	9.9	20.8	7.9

$$I_W = \frac{(I_A - I_S \cdot (1 - p_{IW}))}{p_{IW}} \quad (6)$$

where,

I_W, I_S, and I_A are interception ratios for fall/winter, spring/summer, and for a full year respectively, and

p_{IW} is the proportion of the annual interception attributable to the fall/winter period. As shown in Appendix B, the value of p_{IW} is taken as the proportion of rainfall p_{RW} that occurs in the fall/winter period multiplied by a factor of 0.8.

b) If only annual interception was reported then the winter interception was calculated as

$$I_W = I_A \cdot p_{IW} \quad (7)$$

Based on the above calculation, spring/summer interception was then determined as

$$I_S = \frac{(I_A - I_W \cdot p_{IW})}{1 - p_{IW}} \quad (8)$$

2. This basic data set is reported in **Table 5a**. For Gray and Carnation Creeks, the recovery data were calculated directly in comparison with the reference stand at each site (**Table 5b**). Winter recovery ratios were calculated using winter interception of the immature stand divided by that of the reference stand, etc. For the immature Vancouver Island stands the interception data first had to be adjusted to the reference regime as follows.

a) The interception data were adjusted to the Nanaimo River regime by two ratios:

i) a general ratio to adjust mean site conditions

Table 5b. Rainfall interception recovery: effects of season (all sites) and choice of reference stand (unreferenced Douglas-fir sites) on rainfall interception recovery.

Unreferenced stands, Vancouver Island	Adjusted stand height (m)	Stand height (m)	Recovery ratios* 40-m reference, Douglas-fir Fall/ winter (%)	Spring/ summer (%)	Annual (%)	50-m reference, Douglas-fir Fall/ winter (%)	Spring/ summer (%)	Annual (%)	60-m reference, Douglas-fir Fall/ winter (%)	Spring/ summer (%)	Annual (%)
Douglas-fir											
Cowichan Lake 1 (1997)	18.5	16.0	93.8	74.3	86.0	87.4	68.4	79.8	70.5	63.3	67.6
Cowichan Lake 1 (1995-6)	18.0	15.0	114.0	75.2	98.5	106.2	69.2	91.4	85.7	64.1	77.0
Cowichan Lake 2 (1997)	13.5	14.0	91.6	48.7	74.4	85.3	44.8	69.1	68.8	41.5	57.9
Cowichan Lake 2 (1995-6)	13.5	13.0	72.2	37.5	47.7	67.3	34.5	42.3	54.3	31.9	36.7
Campbell River (2001)	33.0	33.0	107.5	89.8	97.3	104.1	82.0	91.4	97.0	75.5	84.6
Campbell River (2000)	33.0	33.0	86.6	100.9	88.4	83.8	92.2	83.0	78.1	84.8	76.8

Referenced stands Vancouver Island	Adjusted stand height (m)	Stand height (m)	Recovery ratios Fall/ winter (%)	Spring/ summer (%)	Annual (%)	Summer (%)
Carnation Creek						
Hemlock	35.0	35.0	100.0	100.0	100.0	Reference
Sitka spruce	11.5	6.0	56.4	49.0	46.7	NA
Gray Creek				Measured		Estimated
Site F (ref. stand)	32.0	32.0	100.0	100.0	100.0	100.0
Site E	20.5	18.0	104.9	77.5	99.2	93.0
Site D	8.8	8.8	62.4	41.8	58.7	55.0
Site C	5.5	5.5	41.6	17.5	28.4	16.0

Gray Creek snow course	Adjusted stand height (m)	Interception recovery (%)	Stand height (m)	Snowmelt recovery (%)
A	2.5	7.5	2.9	27.5
B	NA	NA	3.0	45.3
C	NA	NA	2.9	57.2
D	NA	NA	4.2	55.7
E	14.6	89.8	14.6	97.3
G	1.2	10.1	1.2	13.3
H	8.8	54.5	6.7	87.1
I	3.6	19.8	4.1	39.6
J	9.5	39.2	5.7	72.6
F	27.5	100.0	32	100.0

* For Douglas-fir stands, recovery is relative to McMinn with regime adjustments (Table 3).

to Nanaimo River regime as reported, using long-term mean precipitation at Campbell River;

- for the Campbell River site, Nanaimo River rainfall for 1951/53 is higher than long term mean rainfall at Campbell River airport by a ratio of 1.08, thus Campbell River data are divided by 1.08;
- for the Cowichan Lake site, in 1952 Cowichan Lake received higher precipitation than Nanaimo River, also by a factor of 1.08 (Table 3), thus Cowichan Lake data were multiplied by 1.08.

ii) a ratio to adjust for differences between long-term mean conditions and conditions specific to the year in which the interception data were collected.

b) The adjusted interception losses were then compared to the simulated reference stand data for various reference stand heights to calculate recovery ratios.

c) Where appropriate, alternatives were considered in order to make sense out of the data from the Campbell River site.

All recovery curves were developed using a modified Chapman-Richards curve (Sit and Poulin-Costello 1994), which was found to provide a good fit to the snowmelt recovery data (Hudson 2000b). The recovery curve is a modified form of the Chapman-Richards curve in which

Table 6. Coefficients of recovery curves for Equation 9, and some site factors that might account for the different curves.

		Asymptote	Threshold	b	c	R^2
Gray Creek						
Winter rain only	1000 m a.s.l. East coast regime.	100	0.0	0.226	2.83	99.0
Rain on snow		100	2.1	0.189	1.25	99.0
Vancouver Island						
Winter rain, 60-m reference	200 m a.s.l. East/west coast regimes. Mix of species.	94	0.0	0.150	2.99	79.2
Winter rain, 50-m reference		100	0.0	0.260	10.81	91.3
Summer rain, 40-m reference		100	0.0	0.140	4.16	98.2
Summer rain, 50-m reference		100	6.0	0.090	1.25	79.1
Lumped data (winter)						
Upper bounding curve	Lumped data, rainfall recovery: use if nothing is known about site.	120	0.0	0.140	1.40	NA
Mean rainfall		100	0.0	0.160	2.07	79.3
Mean rain-on-snow [a] (R2b, low rain-on snow)		100	3.6	0.130	0.78	76.5
Lower bounding curve		80	5.0	0.160	1.39	NA
Summer recovery (lumped)	Gray Cr. + Van. Island (40 m).	100	0.0	0.115	2.58	93.4
Summary curves	**Application**					
S1 (from Hudson 2001b)	Snowmelt.	100	Variable	0.21	0.74	85.7
R1a, rainfall recovery	High elev. rainfall.	100	0.0	0.226	2.83	99.0
R1b, rain-on-snow recovery	High elev. rain on snow.	100	2.1	0.189	1.25	99.0
R2a, rainfall, winter, 2nd-growth referenced	Low rainfall (2nd-growth referenced). [a]	100	0.0	0.167	2.47	NA
R3, summer + winter rainfall, old-growth referenced	Low rainfall (old-gowth referenced), general summer recovery.	100	0.0	0.107	2.11	97.5

[a] Because the R2 Curve had no alternate solution, the "Mean - rain-on-snow" curve is suggested to act as R2b.

an offset was introduced to allow for a non-zero X-intercept. The recovery curve is of the following form:

$$R = a\left(1 - e^{-b(Ht - T)}\right)^{c} \qquad (9)$$

where,

R is the recovery ratio (expressed as a percentage),

T is the recovery threshold for snowpack accumulation, the stand height at which recovery begins, in metres, and

b and c are curve fitting parameters that define the shape of the curve.

The parameter a is the asymptote.

Previously the recovery curve was presented with an asymptote of 100%, under the assumption that recovery will always tend toward 100%. While that might be theoretically true, it might not always occur in practice. As the analysis of the Gray Creek data showed, in which the storm threshold was varied, it is possible to have greater than 100% recovery depending on the selection of the reference stand and on how the data are treated.

The Fortran program used to do the curve fitting calculates the curve coefficients for a range of offsets and selects the coefficients that yield the minimum sum of squares due to error (SSE). It then reports the coefficients for each increment of the threshold. The program was altered to allow for the user to select a range of asymptotes and to report the same results at each increment of the asymptote as well. This allows for the possibility that a stand might be over-recovered, or that it might never achieve full recovery depending on how the reference stand is selected. This approach allows for a much larger range of management options which will ultimately be of greater utility than the restrictive approach used thus far. All results of curve fitting are given in **Table 6**, and are reported as coefficients only, because all recovery curve equations are of the same form as Equation 8.

Seasonal effects at Gray Creek: toward integration of rainfall and snowpack recovery

The application of separate winter and summer recovery curves at Gray Creek was relatively straightforward. There

is little difference between measured annual and winter recovery at Gray Creek, but this is because only three summer storms were monitored. Site C (5.5-m stand) was not operating during the summer storms. Analysis of the meteorological record shows that about half of the precipitation falls as rain and half as snow. Of the rainfall, 72% falls in the fall/winter period, and 28% in the spring/summer. The summer storms that were monitored were only 5% of the total rainfall in the period of study. However, interception that was measured during those storms was 11.4% of the total storm interception measured at the old-growth site. As an alternative, and to provide data for Site C, summer interception was calculated using the method described above. There were substantial differences between measured and calculated values: measured summer recovery at Sites D and E were 41 and 76%, compared to calculated values of 55 and 93% respectively.

The division of recovery into seasonal components makes intuitive sense because the fall/winter rainfall recovery can be combined with the snow recovery data to give a fully integrated rainfall–snowmelt–rain-on-snow model (**Figure 10**). The curve fitting program yields a table of coefficients for each set of recovery data that is analyzed. In other words, there is not a unique solution for each recovery curve that is fitted in this way. Instead, the results often suggest several alternate solutions. In the case of the rainfall/snowpack interception recovery data, the table of coefficients shows a double minimum SSE (**Figure 11**), suggesting two different recovery curves. Both equations fit the data equally well and the two curves merge at a stand height of 5 m.

Recall the following equations given by Hudson (2000b) to calculate the recovery threshold for a given snow accumulation zone:

$$T_{ROS} = \left(D/100\right) + 0.5 \qquad (10)$$

for the 300–800-m elevation band (i.e., the rain-on-snow zone), and

$$T = \left(D/100\right) \qquad (11)$$

for elevations above 800 m,

where,

D is the maximum snow depth in centimetres, which usually occurs around 01 April.

Gray Creek is in Snow Accumulation Zone 4, and with a recovery threshold of 1.4 m, the expected threshold for rain-on-snow snowmelt is 1.9 m. Therefore it is reasonable to assume that Equation R1b with a threshold of 2.1 m represents rain-on-snow rainfall recovery, and that Equation R1a with a threshold of 0 m represents rainfall recovery with no snowpack at the same elevation.

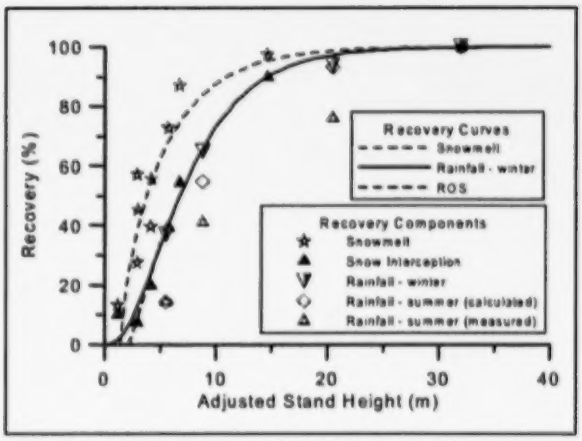


Figure 10. Seasonal recovery components at Gray Creek.

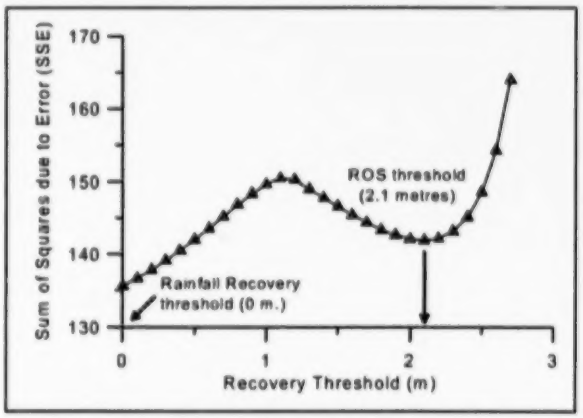


Figure 11. Two possible solutions for a recovery curve based on the same data set.

Applying the variable reference stand approach on Vancouver Island

Initial attempts to calculate recovery for the Douglas-fir stands were not entirely satisfactory because there were no appropriate reference stands that were monitored concurrently with the immature stands. This created difficulties in interpreting the results because it was not possible to reconcile the behaviour of the Campbell River stand with that of the Cowichan Lake stands. The results of interception studies were reported for different years and the sites are far enough apart that they might be under different regimes. In addition, the properties of the original stand at each site are not known. Among the Vancouver Island sites the only properly referenced immature stand is the young Sitka spruce at Carnation Creek that is

referenced to the mature western hemlock stand. The recovery ratio for this stand may be used to judge the value of the modelled results. The rainfall recovery curves for Gray Creek can also serve as a basis for comparison; while representing a different climatic regime, they are based on a measured reference stand at the same site.

Initial attempts to apply the model based on McMinn's data were partially successful. During the process of analyzing the data it became clear that the same reference stand could not be applied to both sites at the same time. However, if the Campbell River stand was assumed to have a reference stand 10 m shorter than the Cowichan Lake sites, the resulting recovery calculation produced comparable results. This strongly suggests that the site potential is greater at the Cowichan Lake site than at the Campbell River site.

Using the approach described above, the Vancouver Island data were used to calculate recovery relative to reference stands of 40-m, 50-m, and 60-m stand height, for both winter and summer recovery. Note that for a reference stand of 60 m applied to the Cowichan Lake sites, the equivalent reference stand for the Campbell River site is 50 m, etc. If the reference stand height is set at 60 m (50 m for Campbell River) the resulting recovery curve for winter rainfall recovery seems to agree well with measured data (**Figure 12**). It also conforms to the accepted form for a recovery curve in which the recovery approaches 100% for progressively greater stand heights. Alternatively, if the reference stand height is 50 m (40 m for Campbell River), the Campbell River stand achieves full recovery, while the juvenile 15-m stand at Cowichan Lake becomes over-recovered relative to the modelled stand as well as to measured old-growth stands at both Gray and Carnation Creeks. This suggests that the fall/winter interception characteristics of old-growth stands at Cowichan Lake and at the Campbell River site are well represented by the modelled stands of 60 m and 50 m respectively.

Under the alternative scenario, the Cowichan Lake and Campbell River sites are compared to the simulated reference stands of 50 m and 40 m to derive recovery data. The result of this comparison is very much like the result of applying a design storm criterion to filter out the effect of small storms on the recovery curve at Gray Creek (**Figure 13**). In both cases the result is that stands in the range of about 15 to 30 m are over-recovered relative to old growth. At Gray Creek this occurred because second growth was found to out-perform old growth at intercepting rain during the larger storms. At Cowichan Lake, the result was due to the specific stand being over-recovered relative to the chosen reference stand.

The assessment of summer rainfall recovery was done in a similar way. As noted earlier, while the reference stand model based on McMinn's data seemed to be fairly consistent when applied to winter rainfall recovery, it was less so for summer recovery. In particular, in addition to using a different reference stand height in order to compare the Campbell River and Cowichan Lake stands, it was also found that while the summer interception at Cowichan Lake was well represented by the Nanaimo

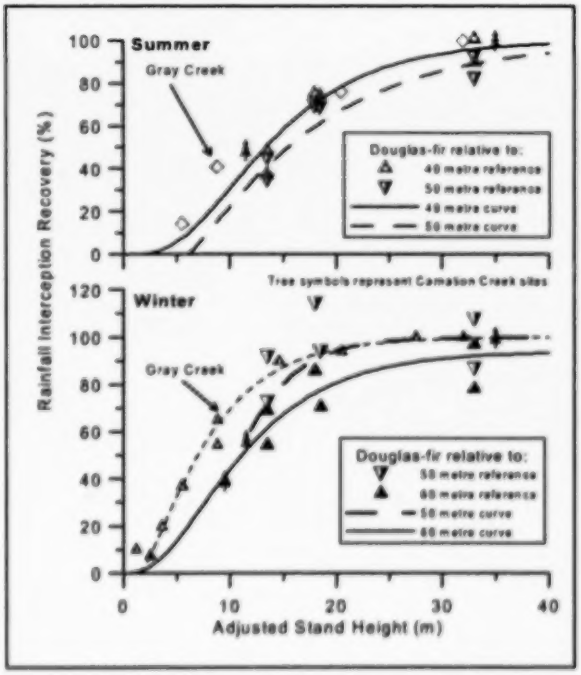


Figure 12. Results of varying the reference stand for Douglas-fir and its effect on the recovery curve.

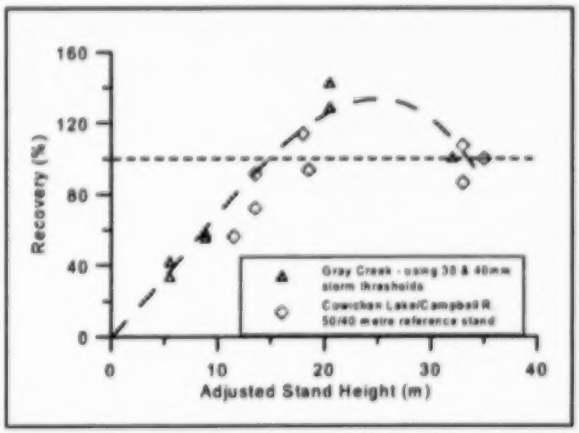

Gray Creek - using 30 & 40mm storm thresholds
Cowichan Lake/Campbell R. 50/40 metre reference stand
Recovery (%)
Adjusted Stand Height (m)

Figure 13. Effects of reference stand criteria on the recovery curve.

River regime, the Campbell river stand appeared to be more like Rothacher's old-growth stand in terms of the differences between summer and winter interception. For example, Rothacher reported summer interception of 24% for 60-m old growth, which becomes 35.4% when the regime adjustment is applied. This is 70% of the predicted interception of 50.1% based on the McMinn model. Applying a scaling factor of 0.7 to the modelled old-growth data for the Campbell River stand makes the summer recovery at that site comparable to that of Cowichan Lake. As above, reference stands of 40-m, 50-m, and 60-m stand height were applied to the Douglas-fir data. A reference stand height of 40 m produces a recovery curve that agrees most closely with observed recovery data from Carnation Creek (Figure 12). It also agrees closely with measured recovery at Gray Creek; therefore, in spite of uncertainties concerning the representativeness of the data it seems reasonable to accept the measured recovery and reject the calculated values. This then results in a single recovery curve for summer rainfall interception.

The difference in reference stand height between summer and winter recovery for the Douglas-fir stands at Cowichan Lake and Campbell River may seem contradictory, however it was noted that the model was considered less reliable for summer than winter interception, possibly because summer interception is more sensitive to stand differences than winter interception. In addition to this, it has also been noted that the summer interception data reported by Spittlehouse is actually for a six-month period that includes the spring, whereas summer interception reported by McMinn was for June to August. While an attempt was made to compensate for the difference, the model probably overestimates interception for the spring/summer period.

Summary of the Approach

To summarize the results as much as possible, the rainfall recovery data appear to form three distinct recovery curves (**Figure 14**):

- **Curve R1**: The curve based on fall/winter rainfall interception at Gray Creek can be viewed as an upper curve for rainfall recovery based on an old growth control, including all storms regardless of storm size. Site elevation is 1000 m.
- **Curve R3**: The curve is based on a combination of summer rainfall interception recovery and winter rainfall recovery under Douglas-fir, assuming that the reference stand should be old growth. The data are based on gross interception regardless of storm size, as with R1. Mean site elevation is 200 m for winter recovery. Data were lumped with summer recovery because the two sets were found to be collinear. For summer recovery the curve applies to all elevations and all species, etc.
- **Curve R2**: There is an area between Curves R1 and R3 where the data that form the two curves overlap. There is a degree of uncertainty in the data due to the fact that reference stands were simulated as opposed to measured. The recovery data from the juvenile Sitka spruce at Carnation Creek also falls into this zone. This can be thought of as an alternate low elevation curve that is based on second growth as a reference stand, rather than on old growth.
- **Over-recovered**: As noted earlier there is a tendency for some second-growth stands to be over-recovered relative to old growth. This is particularly true of managed second-growth stands that tend to have very uniform canopies compared to old growth. Although difficult to formulate, this aspect should be recognized in a method to assess hydrologic recovery. This tendency may be limited or may be common to managed stands and therefore deserves further investigation and/or documentation.

Rainfall interception recovery of a forest stand is a ratio of the current interception capacity over the potential of the original stand (or alternatively, a reference stand) to intercept rainfall. For this reason it should be independent of species. Even though different species have different interception characteristics, the relative effect of forest harvesting at a given site should therefore be a function of the size of the trees, assuming that the same species mix is re-established at the site. The analysis that was done on the interception data from different sources supports this—there was no clear distinction between species.

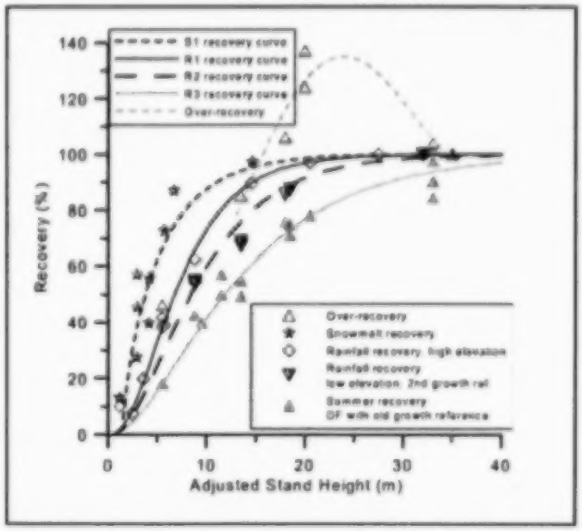


Figure 14. A set of recovery curves that together form the basis of a method to determine full hydrologic recovery, under a range of management scenarios.

The factor that is most likely to affect recovery is elevation, because it controls both precipitation and air temperature (and hence, evaporation), as well as site index. The evidence strongly suggests that the difference between Curves R1 and R3 is due to elevation. The Gray Creek sites are at a mean elevation of 1000 m, while the average elevation among the Vancouver Island sites is about 200 m. Data used in this report would suggest that old growth in an east coast regime could intercept about 30–40% of rainfall, and about 20–30% in a west coast regime. Thus, interception for the old-growth hemlock at Carnation Creek is on the high side, while for the high-elevation, old-growth, subalpine fir-hemlock-cedar at Gray Creek, it is on the low side. In the fall, evapotranspiration rates (and therefore, interception losses) are expected to be much lower at high elevations than at low elevations. Therefore, all other factors being equal, this would point to elevation as the factor distinguishing the two curves. There is no reason, based on the existing data, to further subdivide stands according to rainfall regime, species, or site index. While these factors have been controlled for in the experimental design of the Gray Creek study, they are not well controlled in the Vancouver Island studies. The model based on McMinn's data from Nanaimo River has reduced but not eliminated the sources of uncertainty.

Alternative Approach

As the reader will note, every effort has been made to provide a logical approach to the formulation of rainfall recovery curves such that they can be applied to meet a variety of management objectives; they are based on good, albeit limited, data. The reason for doing this is in part an effort to provide a platform for further research and validation studies. Once this has been done, or as it proceeds, the method of assessing hydrologic recovery can be updated and thus applied with greater confidence across larger areas within coastal British Columbia and the American Pacific Northwest.

In addition, this research provides a milestone in the sense that this is the first time that a more comprehensive research-based method for assessing hydrologic recovery can be offered as an alternative to either the method in BC Ministry of Forests' *Assessing Snowpack Recovery in the Vancouver Forest Region* (Hudson 2001b) or the Interim Method that is given in the *Coastal Watershed Assessment Procedure Guidebook (CWAP)* (BC Ministry of Forests and BC Ministry of Environment 1999). As such it constitutes the best science-based information available at this time. To many proponents this is a very important consideration. However, if this seems too prescriptive or if the reader for any reason does not agree with the interpretation given for the different curves, an alternative approach is offered:

- Lumped data set with bounding curves (Table 6, **Figure 15**): All data used to develop the formulation that is described above and that appears in Figure 14, were lumped together to produce a set of four curves:

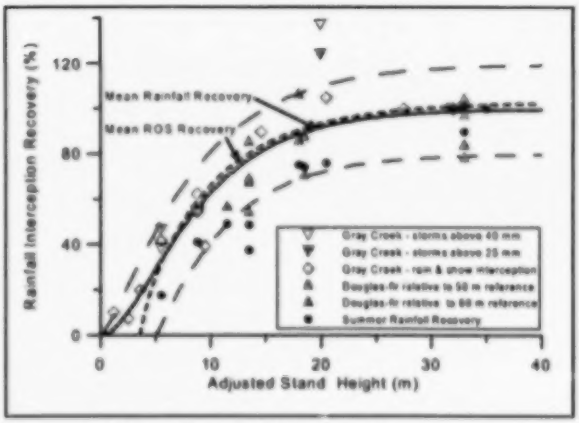


Figure 15. Alternative rainfall interception recovery curves based on lumping together all rainfall recovery data, with upper and lower bounding curves. Note that the relationship between summer recovery and winter recovery relative to an old growth reference is shown on this graph.

  - As with Curve R1, the curve fitting results indicated two possible solutions that appear to suggest rainfall and rain-on-snow recovery curves. The two curves cross (as opposed to merging) at a stand height of about 6 m. Above that height they could be considered interchangeable.
  - Upper and lower bounding curves that encompass 90% of the data points. Out of necessity these curves have asymptotes of 80 and 100%.
  - While the mean curves both have asymptotes of 100% (this was not assumed, but is a result of curve fitting), the range between the bounding curves at the upper end is very close to the 95% confidence interval of the mean rainfall interception recovery measured at the old-growth site at Gray Creek (Figure 4).
  - The rain-on-snow curve has some utility because it is very close to the R2 Curve toward the upper end. Because the data analysis of the winter rainfall recovery data from the Vancouver Island sites did not indicate more than one solution for each data set, then this curve is valid as an rain-on-snow recovery curve for low elevations (i.e., the lower end of the rain-on-snow zone).

Beyond this, if the proponent chooses to use these curves to assess hydrologic recovery, he or she must supply the rationale for such use.

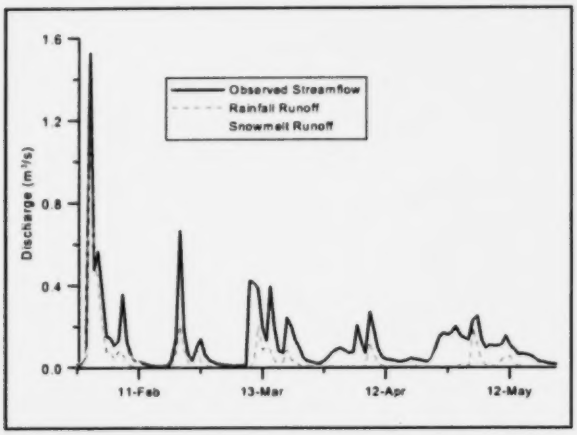


Figure 16. The components of streamflow that occurred as a result of snowmelt and rain-on-snow events, as determined by the UBC watershed model.

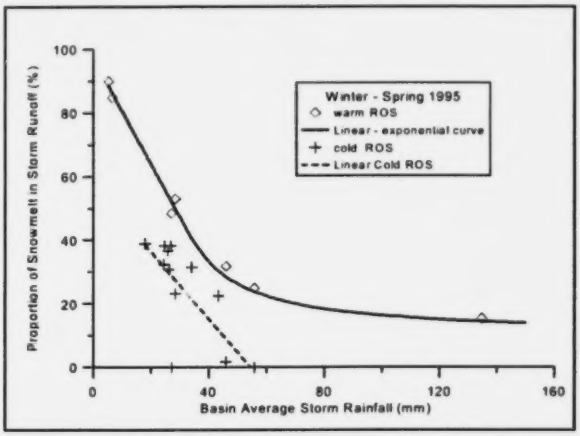


Figure 17. The proportion of snowmelt in daily runoff during rain-on-snow at upper Gray Creek is a function of mean daily rainfall.

Determination of Hydrologic Recovery for Rain-on-Snow

Using the University of British Columbia (UBC) watershed model (Quick et al. 1995), streamflow at Upper Gray Creek was modelled for a period of time, including the 1994–95 water year. The period between January and May 1995 included 18 rain-on-snow events with a wide range of conditions (Hudson 2000b). The modelling results revealed the breakdown of the components that contributed to the flow (**Figure 16**). The proportion of the runoff that was derived from rainfall and snowmelt in each event was related to the total daily rainfall that contributed to the rain-on-snow event, and to the mean daily temperature.

The rain-on-snow events can be generally divided into two types: the warm rain and cold rain types. With cold rain, there is insufficient energy available to melt any snow, and the runoff consists almost entirely of rainfall. Although there is some overlap between the two types, it appears that if the mean daily temperature is at least 1.5°C, the event is of the warm type. Under these conditions, there is a negative linear–exponential relationship between the proportion of the runoff contributed by snowmelt and the total basin average storm rainfall P_R (**Figure 17**). An equation to describe the proportional contribution of snowmelt outflow to the total storm runoff is:

$$p(S) = 97.1 - 1.7(P_R) \qquad (12)$$

for P_R <34 mm, and

$$p(S) = e^{\left(2.32 + \left\{47.4/P_R\right\}\right)} \qquad (13)$$

for P_R >34 mm,

where,

$p(S)$ is the proportion of the runoff (expressed as a percentage) that is contributed by snowmelt.

A relationship for cold rain-on-snow is also suggested although it is poorly defined (Figure 17). More work is required to determine what form that relationship will take. The linear–exponential function described by Equations 9 and 10 look very much like a similar relationship given by Church (1988) for determining the relative contribution of snowmelt to the water yield of a rain-on-snow storm. Church presents the relationship as a family of parallel curves based on temperature and wind conditions. This suggests that upon further analysis, this relationship could be developed more completely to include all rain-on-snow storms in a temperature based model, as opposed to simply dividing them into two classes.

Implementation

A framework for modelling hydrologic recovery due to rainfall, rain-on-snow, and snowmelt in a watershed with an appropriate elevation range can now be formulated from Equations R1b and R2b and Equations 10 to 13. The method involves a simple blending of the equations across the rain-on-snow zone between 300 and 800 m elevation. For the general situation in a "typical" watershed the method can be applied as follows:

- Determine appropriate values for thresholds T_{ROS} and T using Equations 10 and 11.
- 0–300 m: Assuming rainfall dominated, use Equations R2a or R3.

• 300–800 m: Assuming rain-on-snow is applicable, the rainfall component of rain-on-snow is derived from blending Equations R2b and R1b as follows:

– Assume that Equations R1b and R2b apply to rain-on-snow at 1000 and 300 m respectively, with T_{ROS} thresholds varying according to elevation and snow accumulation zone.

– Select equation coefficients from Table 6, substituting the appropriate threshold values for the thresholds given in the table. Note that the thresholds vary with elevation for a given zone.

– Blend the two equations across the rain-on-snow zone between 300 and 800 m using a weighted average. Determine the weighting factor by linear interpolation between 300 and 1000 m:

$$R_{RC} = F(R2b) + (1 - F)(R1b) \qquad (14)$$

where,

F is a weighting factor such that F=1 at 300 m and F=0 at 1000 m, and

R_{RC} is the resulting recovery due to the rainfall component of rain-on-snow.

– Full hydrologic recovery for the rain-on-snow zone can then be evaluated as follows :

$$R_{ROS} = \frac{p(S)}{100} \times R_S + \left(1 - \frac{p(S)}{100}\right) \times R_{RC} \qquad (15)$$

where,

R_S is the snowmelt component of rain-on-snow recovery as determined by the snowmelt recovery Equation S1.

• Above 800 m: Use Equation S1.

The method described above has the potential to be applied on a storm-by-storm basis if a detailed analysis is warranted, and assuming data are available. However, hydrologic recovery is usually determined for stands under standardized conditions, and not for individual storms. Therefore the determination of a hydrologic recovery equation for the rain-on-snow zone in a watershed must be based on an analysis of the average frequency of storms of a given size that result in rain-on-snow conditions. This can probably be regionalized, but requires an accepted standard design storm on which to base the value of $p(S)$. Some options include:

• average size of storms that result in rain-on-snow conditions, and

• rain-on-snow storm of a given return period such as the 1- to 1.5-year event.

There are important issues about how to evaluate such a design storm:

• storm volume of all storms known to result in rain-on-snow conditions; or

• enhanced storm volume, i.e. storm volume + resultant snowmelt contribution.

Wherever possible such decisions should be based on an objective evaluation of the options. This implies that the different options should be applied to several watersheds as case studies, followed by a critical analysis of the results of those studies. By using examples that are familiar, the option that produces the most consistent results is likely to be the most logical choice. For this reason it is beyond the scope of this report to discuss implementation of the method. This report is part of an ongoing series about developing the method of assessing hydrologic recovery and about its application in evaluating the effects of forest harvesting on streamflow. Implementation of the method is currently under investigation and will be reported in a subsequent extension note.

DISCUSSION

Several assumptions had to be made to interpret the data. The interception model that was developed helped to identify which assumptions were valid. For example, a comparison of measured interception under various old-growth stands to the modelled interception showed that there was a fundamental difference in the hemlock stand that makes it unsuitable to act as a reference for Douglas-fir. This is probably because the shade-tolerant nature of the hemlock greatly increases its interception capacity compared to Douglas– fir. Another assumption was that the stands, once mature, would approach 60 m in height, but the model showed that this is unlikely in the case of the Campbell River stand. The data reported by McMinn are also useful in addressing this issue because they show the variability in old-growth characteristics that occurs within part of a watershed. All the stands that were monitored were in the range of 300–350 years old. Stand heights ranged from 25 to over 70 m, with the tallest stands occupying the valley bottoms. If we tried to relate recovery of any site in the watershed to the interception characteristics of a 70-m valley bottom stand, the result would be far too conservative; in fact most of the stands could never possibly reach recovery according to such a criterion.

While the simulations based on McMinn's measurements of interception under old growth at Nanaimo River have reduced the uncertainty in assessing recovery of the various Douglas-fir stands, there is no real substitute for a concurrently measured reference stand. The data obtained at Gray Creek were properly controlled, and while the sampling was somewhat less rigorous than that used by Spittlehouse, there is less uncertainty in evaluating recovery. The measurement error might affect the precision of the result, but not its accuracy. Furthermore, the effect of species is controlled for at the Gray Creek site

but not at the Vancouver Island sites. Nonetheless, the model was able to identify major species-related differences in interception by comparing the hemlock stand to other measured old-growth stands. In the final analysis, the remaining uncertainty has been minimized by pooling the data; the resulting generalized recovery curves can be used to achieve specific management objectives.

It should be noted that the recovery data for Douglas-fir was based initially on an estimate of what the interception characteristics of an old-growth reference stand should be like. However, it has been shown that old growth might not always be the most appropriate reference stand to use as a benchmark against which to measure recovery. In the case of Gray Creek, there is a clear tendency for the second growth to become over-recovered because it is more efficient at intercepting rainfall than the old growth. The stand in question is a managed stand, having been subject to juvenile spacing. The noted tendency might be generally true of managed stands because they are maintained at a higher and more uniform stocking density than old growth. For this reason, in areas of extensive second growth (e.g., the east side of Vancouver Island) the use of old growth as a reference stand to judge recovery might be inappropriate. For this purpose, two optional recovery curves are given to assess fall/winter recovery for low elevations: R3, with old growth as a reference, or R2, which represents recovery relative to advanced second growth.

R3 represents the result of using a target old-growth height of 60 m for the Cowichan Lake stand and 50 m for the Campbell River stand. This scenario indicates progression toward recovery; the 33-m stand is about 88% recovered and a stand of 18 m height is about 78% recovered. The alternative curve, R2, represents the selection of 50 and 40 m reference stand height. This scenario results in recovery characteristics closer to those of Gray Creek; the 33-m stand is close to fully recovered and the 18-m stand exhibits behaviour whereby in some years it is over-recovered. The recovery curve is still below that of the Gray Creek recovery curve for rainfall/rain-on-snow, but it may be more realistic when applied to low-elevation, second-growth stands. If recovery is to be an assessment of the condition of the stand relative to its hydrologic characteristics prior to harvesting, then to use old growth as a reference would be inappropriate.

Notwithstanding the above discussion, the summer recovery is represented by Curve R3. There are different hydrologic issues related to summer and winter flows, and therefore the separation of hydrologic recovery by season is appropriate. In the summer the main issue is low flows and how forest harvesting might affect those flows. The situation is less complex because snow is not considered, so only one recovery curve is needed. The recovery status according to the R3 Curve may serve as an index of the potential of forest harvesting to increase summer low flows. In the fall and winter the main issue of concern is the potential of forest harvesting to increase peak flows. Analysis of the Gray Creek rainfall recovery data showed how the 18-m stand became over-recovered relative to the old-growth reference stand, and reached a peak at around the 1.2-year event, which is generally accepted as the main channel-forming event. In this case, if this is a widespread phenomenon, then consideration should be given to the tendency for stands in the 18–30-m range to be over-recovered. This is important because if the regenerating forest growth is over-recovered relative to the original stand, then these over-recovered stands will serve to mitigate against un-recovered stands elsewhere in the watershed.

The effect of the hydrologic recovery status of a regenerating stand on potential runoff is relative to the interception capacity of the original stand. The way that hydrologic recovery is defined does not allow for the variability in the interception capacity of different stands. Thus if two regenerating stands of equal area are evaluated at the same level of recovery (say, for example, both stands are found to be 50% recovered) the equivalent clearcut area (ECA) of both stands would be the same. Nonetheless, the effect of the status of each of these stands on streamflow would still be proportional to the interception capacity of the original stand. This is true not only for rainfall recovery, but for snowmelt as well. The snow accumulation recovery is subject to slightly different processes than rainfall recovery (e.g., sublimation and/or melting of snow, and the capacity of the canopy to hold snow as opposed to rain). Consequently there are some differences in interception; snow interception at Gray Creek currently averages about 50%, whereas the same site intercepts <30% of rainfall in the fall and winter. It would make the concept of hydrologic recovery and ECA more physically meaningful if the method could be developed to account for these differences. This is also a potential issue to be aware of in interpreting the results, and an area on which future research should focus.

The concept of hydrologic recovery is based on the idea that the re-growth of a forest canopy will restore the hydrological characteristics of harvested forest stands to those of old growth. The influence of forest canopies on hydrological processes is inherently difficult to measure and characterize, because forest stands are non-uniform, and are composed of living things that interact dynamically with their environment. The interchange of energy and water between the canopy and atmosphere is very complex. An effort has been made to account for as many variables as possible, but inevitably some of that complexity is lost for the simple reason that there is not enough data to sort out all of the variables. Notably, both canopy density and stand height have been accounted for in the composite variable "adjusted stand height".

The need for operational methods that are relatively

simple to apply must be weighed against the need for those methods to be scientifically defensible. It is important to recognize that most operational methods are approximations for this reason. An operational method must be practical; it must be based on a stand variable that is regularly reported and is easy to measure with high precision and without bias. In this sense, stand height is inherently a better variable than canopy density or closure. The fact that stand height correlates better with recovery than canopy density probably reflects the fact that height is a precision measurement, whereas canopy density is highly subjective. There are several methods of measuring it (e.g., moosehorn, spherical densiometer, "fish-eye" photography). All methods produce somewhat different results, with varying levels of precision and observer bias, but there is no standard method of measuring it and consequently it is often estimated (as "crown closure", which is generally higher than measured canopy density).

The concept of hydrologic recovery is routinely used to calculate the ECA of watersheds. It is generally treated as an index of the potential for forest harvesting and regeneration to alter the peak flow response of the watershed in question. A simplified approach such as the method presented here is appropriate for that purpose, because there are other factors that govern peak flow response that are probably more important than minor deviations in forest canopy structure. If anything, the method will tend to be conservative if it is applied without adjusting the height of overstocked stands, because if a stand is under-stocked, this may be compensated by using the patchiness factor. There is no other mechanism to compensate for the effects of overstocking.

One limitation of the analysis is that the calculation of the proportions of runoff supplied by snowmelt and rainfall is based on modelled data from only one site. Although the data are modelled, the model has been shown to simulate snowpack dynamics very well (Hudson 2000b). The relative contribution of snowmelt to any runoff event can be easily verified by examining the changes in the snowpack over time. The proportions are based on a representative sample of the data from that site, from a range of flow and precipitation data representing return periods of up to 2–3 years.

Because of the need to base hydrologic recovery forecasting on standard conditions, the relative proportions of rainfall and snowmelt runoff in total storm flow can be based on a "mean" storm, weighted by the probability that a given storm will fall into a given size class, or on some other criterion. While the mean storm approach may be an accepted method of forecasting recovery based on average storm conditions, it downgrades the weight given to the largest storms which, in a sense, are the most important. This introduces an inherent error according to the difference between mean hydrologic recovery and actual recovery that could be calculated after the fact for a given storm. Because rainfall interception recovery is slower than snowmelt recovery, the recovery specific to a large rain-on-snow storm will be underestimated by the forecasted mean recovery if the mean storm is used. This raises the issue of how to define the design storm so it can be used as a basis for establishing a standard method. If the 1.2-year event (representing bankfull discharge) is to be used, then the error will be minimized for that event, which is considered the most significant channel-forming event. This will require a regional approach for establishing design storms for the operational application of the method.

Hudson (2000b) gave the error in applying the snowmelt recovery curve at 10.6%, based on the standard error of the curve fitted to the overall 7-year mean snowmelt and rain-on-snow melt recovery data. This is also discussed in Appendix A; the 10% "error" due to stand variability is constant and independent of stand height. For rainfall recovery at Gray Creek, an analysis of the distribution of recovery ratios of individual storms showed that there was a basic ±5% error that was not attributable to the stands themselves. The remainder of the variability was in direct proportion to the stand height such that the old-growth stand relative to its own mean interception could be anywhere from 82 to 117% recovered (Figure 4a). If the 5% measurement error were removed that range would be reduced to 77–112%, or ±12%. In contrast, the variability in interception attributable to the stand under the 18-m second growth was ±6.2%. These apparent error distributions were calculated in different ways; rainfall interception recovery was calculated by averaging across storm intensities, over a shorter time frame than snow melt recovery. When calculated in the same way as the mean snowmelt recovery curve, the rainfall recovery curves have lower error (and consequently higher R^2, Table 6) than the snowmelt curve. This suggests that the error due to stand variability at Gray Creek is within ±10%. The error in applying the method at other sites cannot be evaluated without further research to validate the methods.

The heterogeneity of rainfall and the variability of other factors that influence interception (such as wind), are almost certain to generate a large error if the data are used in raw form. Averaging of the data should therefore remove most of that variability, thereby resulting in a data set where the errors are due to the variability in the stand and to measurement error. It may be possible to minimize error, but because forest stands are inherently heterogeneous, our ability to control variability is extremely limited. This is not necessarily error, but can be thought of as uncertainty. We need to make management decisions in spite of that variability. This implies that professional judgement is required to interpret any results based on the application of these methods.

LIMITATIONS

This report describes the current findings of an ongoing regional research initiative that has been in progress for several years, and is far from complete. Therefore the method described has limitations that may or may not affect its applicability. This report, together with Vancouver Forest Region's Technical Report TR-004 *Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region* (Hudson 2000b), provides a basis that can now be built upon with additional studies to test the broad applicability to south coastal British Columbia. Known limitations are listed below, but the list might not be exhaustive.

1. The methods are based on data collected at a small number of sites. General applicability remains largely unknown, although the basic framework for generalizing the method is already in place.

2. There were insufficient data for investigating the effects of such variables as tree species and site index on rates of hydrologic recovery. These issues require further research.

3. The method of blending the rain and snow curves to simulate components of rain-on-snow runoff is based on modeling results that were applied at only one site.

4. A method of blending the rainfall/rain-on-snow recovery curves according to elevation is suggested but not tested. While it is logical to assume that the main factor behind the two curves is elevation, there might be other factors as well.

5. The reference stands for Douglas-fir are simulations as opposed to actual measured stands. However, they are based on measurements done under Douglas-fir stands in the Nanaimo River watershed which appears to be a good reference for the Cowichan Lake sites. But, adjustments were needed to incorporate the Campbell River stand. This always leads to uncertainty.

CONCLUSION

This report describes the second step toward establishing a science-based, comprehensive, integrated approach for assessing full hydrologic recovery for coastal British Columbia watersheds. It builds on an earlier report, Vancouver Forest Region's Technical Report TR-004 *Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region* (Hudson 2000b), that describes a regional approach for applying the snowmelt recovery method (Hudson 2000a). This report is put forward as the best available information, to be used with caution and to be applied using professional judgement. The user should recognize that the method described here has not been widely tested in a research capacity, although the method presented in the earlier report (Hudson 2000b) has been widely applied. To use the method, the proponent should be aware of the limitations listed above, and should consider the application of this methodology in light of these limitations.

Recognizing that forest harvesting and subsequent regeneration have the potential to alter peak streamflow, the concepts of hydrologic recovery and equivalent clearcut area (ECA) provide an index of the changes in hydrologic characteristics of forest stands. The link between ECA and actual peak flow changes is not yet defined, although a start has been made in that direction (Hudson 2002). In the meantime, ECA should still be treated as an index of potential peak flow effects. As a component of a watershed assessment, it is important to keep it in context of the other components, and to recognize the way in which the different components interact.

Notwithstanding the above, the methods described are based on an extensive body of research that began more than 45 years ago. Further, the direction of future research to fully develop this methodology is well established. The primary goal of future research should be to validate the integrated hydrologic recovery method by conducting similar research trials in representative coastal watersheds in other parts of the region.

Other areas requiring research include:

- Synoptic validation of snowpack extent in relation to snow courses to establish the applicability of snowmelt recovery using satellite imagery.
- Establishment of a method to account for differences in interception capacity, to normalize the effect of hydrologic recovery on potential runoff production.
- Investigate the relationships between site index and hydrologic recovery.
- At the same time, it is essential to establish the link between changes in ECA and documented changes in streamflow that can be reasonably attributed to forest harvesting and regeneration.
- Development and testing of a numerical hydrologic simulator as a tool for forecasting effects of forest harvesting and roads on streamflow.

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APPENDIX A

AUTHOR'S NOTES: IMPLEMENTATION OF HYDROLOGIC RECOVERY METHODS

Since the Vancouver Forest Region released Technical Report TR-004 *Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region* (Hudson 2000b), the method has been widely implemented. It is assumed that anyone using this method would apply his/her professional judgment in its application. The heterogeneity of a watershed's climate, soil properties, geology, etc., as well as the genetic variability among tree species, all contribute to a large unexplained variability in the influence of regenerating forest stands on site level hydrology. The fact that we must use a simplified approach to assessing hydrologic recovery is a direct consequence of that variability. In other words, we might eventually be able to account for all those factors that cause the variability but the resulting method would be far too complex to apply operationally. It is for this reason that professional judgment is needed to interpret the results of applying hydrologic recovery methods.

The method described in TR-004 is based on snowmelt during rain-on-snow and radiation melt events at Gray Creek between 1993 and 1997. This data set is shown in Figure 5 in TR-004 (reproduced here as **Figure A1**). For example, according to the curve, a 4-m stand is 55% recovered. The scatter of the observations indicates that the recovery could be anywhere between 20 and 85% depending on the specific combination of variables that had occurred at that site in any given year. Thus by including the total variability in the observations, the 4-m stand is 55 ± 32 % recovered.[1] Because that data set is made up of repeated measurements (eight events) at each of 10 snow courses, the points in Figure 5 are not entirely independent. If recovery is averaged over the 8 events at each snow course, the resulting data set consists of 10 points that are completely independent of each other, as shown in Figure 6 (reporduced here as **Figure A2**). Using the error bands in Figure 6, recovery for the 4-m stand is 55 ± 10 %. This means that about two-thirds of the variability in the response of snowmelt to that stand is due to climatic variability. In both Figure 5 and Figure 6, the data points form a uniform band about the recovery curve, suggesting that both components of variability are independent of stand height. Therefore the unaccounted variability in snowmelt recovery is 10%, regardless of the stand height. The additional 22% variability is due to climatic conditions and can therefore be ignored because it has nothing to do with the stand.

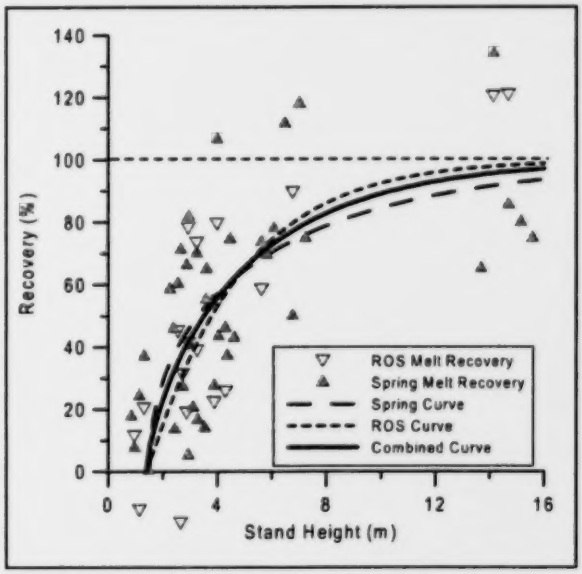

Figure A1. Spring and rain-on-snow (ROS) melt recovery, with separate and combined curve fits. (Figure 5 in Hudson 2000b)

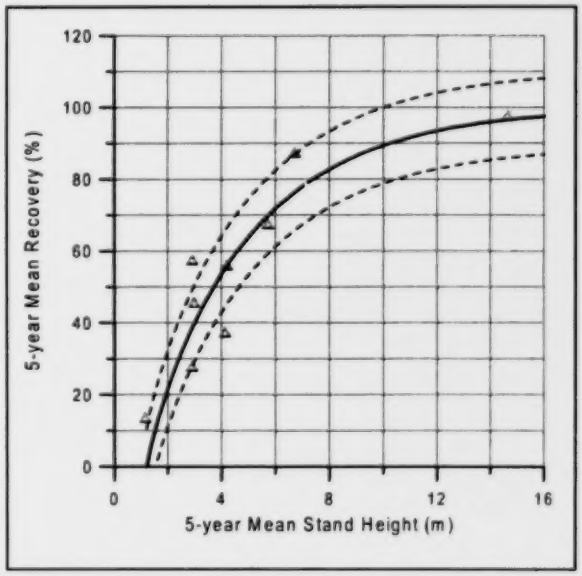

Figure A2. Combined spring and rain-on-snow melt recovery curve based on averaged recovery data. The dashed lines represent ± 1 s.e. about the curve. (Figure 6 in Hudson 2000b).

[1] Because the dependent variable is expressed as a percent, then the absolute error and the relative error as a percentage of the value are both percentages. This could be confusing, particularly when the value is around 50%, which makes both absolute and relative error the same. I have used absolute error.

Any forestry technician or researcher who has measured natural forest stands can appreciate the inherent variability in those stands, and particularly among young stands. The recovery curve represents the mean response. For large watersheds with lots of forest openings close to the threshold height there is almost certainly a high degree of variability in how those stands affect the hydrology of the site. That variability is at its maximum at the time the stand is just beginning to alter its hydrologic regime, because that effect is very tenuous and difficult to detect separately from the effects of local topography. However, taken across the landscape level, the effect of all such "marginal" stands will approach the average. That is what the hydrologic recovery method aims to do: to estimate the mean effect that all stands of more-or-less equal height have on site-level hydrology. As such it forms part of a methodology to examine the cumulative effect of a large number of small effects dispersed throughout the watershed. It is accurate for large sample sizes, and its accuracy declines as the sample size (or watershed area) decreases, although the error is not likely to exceed 10%. If there is some doubt as to the applicability of the curve to a specific stand that is at or near the threshold, recovery may be reported as a possible range of values. Either way, the professional proponent should provide a clear rationale for his/her choice.

The recovery curve, based on the Chapman-Richards curve, is actually an S-shaped curve that depicts early tree growth as gradual; this is followed by a period of rapid growth. In the case of the snowmelt recovery curve, the bottom of the S-curve (i.e., the gradual part) is truncated by the snowpack; that is, all trees below that threshold are covered over. It may be difficult for some to visualize the large increment in control that the stand apparently exerts for a relatively small increment in height. The reason why this occurs is that the threshold is based on the mean annual peak snow depth. However, the point where the melt rate is at a maximum occurs after at least part of the snowpack has melted. For example, if the threshold is 1.8 m, and the stand grows by up to 1 m/y, it could theoretically achieve 30% recovery within one year after clearing the threshold.

This may seem incredible, but it is critical to understand that the snowmelt and/or the potential for rapid melt to occur is probably at a maximum when the snowpack is at least half gone. So, the trees cannot influence the snowmelt process when they are totally covered by the snowpack; they do not have to because the snowpack is not ready to melt rapidly either.

The pack first consolidates and gradual melt occurs until the depth is down to about 0.9 m. At this point, the snowpack occupies the part of the stand that is most likely growing outward at its maximum rate. (Recall that in juvenile trees, their crowns go right down to the ground, and they do not just grow upwards, they also grow outward, thereby filling up the space between trees). The point where the snowpack becomes discontinuous is a turning point—once this happens, the melt rate is greatly increased due to the sudden increase in exposed surface area, if in fact the snowpack is exposed at that time.

Forest stands are dynamic—and juvenile ones are particularly so. We often forget that trees are living things, not inanimate objects, and they do a lot more to alter snow and rain interception conditions than just to sit there with their arms out, so to speak. One important aspect of what they do is to gather and re-radiate heat. That has a large effect on snowpack dynamics. In areas where snowpacks are not particularly deep (e.g., Snowpack Accumulation Zone 4 on the east side of Vancouver Island), a small increment of growth can have the effect of totally altering the thermodynamics of a snowpack that is primed for rapid melt. This is not just due to the size of the trees, but also to the fact that they are developing a canopy together with neighbouring trees. The development of individual tree crowns and the development of a canopy are two different processes.

There comes a point where the canopy develops to the extent that the snowpack, once it becomes discontinuous, is ***under*** the canopy as opposed to ***in*** the canopy. This does not necessarily occur gradually, but may occur over the course of one or two growing seasons. As far as the snowmelt recovery is concerned, that change is instantaneous. The stand goes from leaving the discontinuous snowpack exposed to rapid melt to sheltering it in the course of one or two growing seasons. These effects are difficult to quantify, but nonetheless they are very important in their influence on watershed hydrology. I believe that this process, or something like it, occurs to cause rapid changes in the thermodynamics of melting snow. The question is, how can this be quantified?

APPENDIX B

NORMALIZING INTERCEPTION DATA

The main difficulty is interpreting the interception data from various sources is that only summary data are available, and in each case the data are summarized somewhat differently. Most studies identify seasonal components separately, but define the seasons differently. McMinn (1957) reported annual and summer (June–August) interception, whereas Spittlehouse[1] reports annual and spring/summer (April–September) interception. Because the time periods for reporting seasonal interception are different, a normalization procedure was developed, primarily to separate interception into spring/summer and fall/winter periods. The fall/winter period was of primary interest in this study because the major storms occur at that time.

This procedure was based on precipitation data from a few key sites and on interception data where the seasonal components are known. The purpose was twofold:

1. to adjust the McMinn interception data to provide an interception model suitable for deriving seasonal recovery ratios from data reported by Spittlehouse, and
2. to calculate seasonal interception data (specifically, fall/winter) from reports where only annual or annual and summer interception values are reported.

The main goal of the analysis was to differentiate fall/winter recovery and spring/summer recovery periods. Therefore for the purpose of this analysis, the following seasons are defined:

Fall/Winter	W	October–March
Spring/Summer (Spittlehouse)	S	April–September
Fall/Winter/Spring (McMinn)	FWS	September–May
Annual (McMinn, Spittlehouse, Rothacher)	A	

Precipitation data in the form of long-term climate normals can be obtained free of charge from the Environment Canada website. Precipitation normals for Campbell River, Nanaimo, and Tofino were summarized into seasonal totals, and from these summaries some key ratios were obtained (**Table B1**). In addition to this, monthly data were purchased from AES for the same sites for the period 1995–2001 (**Table B2**) so that data obtained from interception studies could be referenced to the precipitation data for the specific time period in which the interception data were collected.

A Working Method to Derive *W* and *S* Components from Summary Data

The underlying assumption in this analysis is that there is a relationship between the ratio of seasonal to annual rainfall and the corresponding interception ratio. For example, the mean winter rainfall ratio PP_W/PP_A (the proportion of annual rainfall that falls in the fall/winter season) is between 0.7 and 0.75 at most sites. The corresponding interception ratio I_W/I_A is expected to be related to, but not equivalent to, the rainfall ratio. Much of the interception data require a good estimate of seasonal interception ratios to disaggregate annual interception into seasonal components.

The correct way to calculate seasonal interception is to use the measured interception totals in mm (i.e., $I = PP-T-S$) and divide these values by the seasonal rainfall. This can be done if interception is reported for one season and for the whole year if appropriate rainfall data are available. If interception is reported only as a percentage without supporting data, it is still possible to apportion the interception between seasons using the given ratios alone. The following expression can be used to divide annual interception into seasonal components:

$$I_A = p_{IW} \cdot I_W + (1 - p_{IW}) \cdot I_S \qquad \text{(B1)}$$

where,

p_{IW} is the proportional component of interception that occurs in fall/winter relative to the whole year, and

I_W and I_S are the winter and summer components of annual interception, I_A.

All data expressed as percentages.

If annual, winter, and summer interception components are all known, then re-arranging Equation B1 will yield the following expression to calculate the value of p:

$$p_{IW} = \frac{I_A - I_S}{I_W - I_S} \qquad \text{(B2)}$$

Note that a similar value, p', can be calculated directly by a simple ratio:

$$p' = I_W / I_A \qquad \text{(B3)}$$

where,

I_W and I_A are expressed in mm.

This can be done only if measured interception and rainfall data are available.

Using data with measured interception, interception and seasonal interception ratios were calculated using two different methods: the Direct Method and the Working Method (**Table B3** and **Table B4**).

Direct Method: Measured interception data were used to calculate p' :

[1] Spittlehouse 1998, 2001, and see Footnote 1.

- At Gray Creek, all parameters were measured at the site. This allowed p' to be calculated directly as the ratio of winter over annual interception. Similarly, total rainfall during storms in which interception was measured was also divided up seasonally, and a winter rainfall ratio p_R was calculated.
- The interception data for Campbell River and Cowichan Lake are based on annual and spring/summer interception ratios reported for specific years, and monthly rainfall data from Campbell River airport for the same years. Using reported summer and annual interception as a percentage, interception volumes for those periods were calculated from the rainfall data and the winter interception was determined by subtraction.
- The Campbell River rainfall data were used "as-is" to determine interception for the C.R. Douglas-fir plot, whereas the multiplier 1.08 was used as a regime adjustment factor for the Cowichan Lake plots.
- To apply the ratio p' to summary data, it is multiplied by the p_R ratio when interception values are converted back to percentages. In the case of Gray Creek, the summer interception data are derived from only five storms whose total volume was only 7.6% of the total annual storm rainfall. Thus the winter rainfall ratio is 0.924 in this case, while total winter makes up 72% of the total annual rainfall (both storm and non-storm rain).

Working Method: The ratio p was calculated from seasonal interception (as %) using Equation B2. This was applied directly to interception data that were calculated as per the above.

The results of this analysis show that either method can be used to calculate seasonal interception components, depending on availability of data. While the primary goal was to derive a factor to estimate winter interception from winter rainfall ratios, the Direct Method serves to validate the Working Method. To apply either method, the winter precipitation ratio must be multiplied by the winter interception ratio p to derive an adjustment factor that is calculated as follows:

Direct Method

$$p' = 1.09(p_{RW}) - 0.17 \qquad \text{(B4a)}$$

$$p_{IW} = p'(p_{RW}) \qquad \text{(B4b)}$$

Working Method

$$p_{IW} = 0.78(p_{RW}) + 0.14 \qquad \text{(B5)}$$

Application to McMinn Data

Before this adjustment can be applied to the McMinn data, another adjustment factor is needed that will compensate for differences in the length of season. Using monthly data from Nanaimo and Campbell River, the ratios PP_W/PP_A and PP_{FWS}/PP_A were calculated. The relationship between those two variables can be used to estimate the PP_W/PP_A ratio among the McMinn data (**Figure B1b**), according to the following equation:

$$PP_W/PP_A = 58.7\left[PP_{FWS}/PP_A\right] - 31.0\left(PP_{FWS}/PP_A\right)^2 - 26.9 \qquad \text{(B6)}$$

The McMinn data are summarized in **Table B5** and **Table B6**. The original data set consisted of 21 plots that were then organized into classes according to several different criteria, including stand height, site index, and total precipitation. Once again, stand height promised to be the best single classification variable. The plots were grouped into six classes according to 10-m increments in stand height starting with 20–30 m up to 70–80 m. The fall/winter interception was determined by first applying Equation B6, and then Equation B5 to give the final result reported in Tables B6 and B7.

A Model to Derive Reference Stands for Immature Douglas-Fir

Because the calculation of seasonal interception data using both methods is in close agreement (**Figure B2**), the following equation can be used to calculate interception under a Douglas-fir reference stand:

$$I_W = 0.052(SH) + 14.4$$

for stand heights (SH) <46 m, and

$$I_W = e^{0.000747(SH)^2 - 0.0607(SH) + 4.04}$$

for SH ≥46 m (B7)

Summary

There are two possible approaches to determining seasonal interception: a Direct Method and a possible Working Method that can be applied if there is insufficient information to calculate those values directly. The proportional seasonal weighting factor, or interception ratio (p) is related to the seasonal rainfall ratio (p_R). The value of p could be derived from any season, but because the primary interest for coastal British Columbia is fall and winter rain-on-snow effects, the winter interception ratio was determined. Those ratios were calculated from data where both methods could be applied. The ratios were then applied to the McMinn old-growth interception data, thereby using the direct approach to validate the working method.

The two methods used to calculate seasonal interception data produced similar results (Figure B2). Thus two objectives have been achieved: a working method for apportioning seasonal interception has been validated, and a model has been developed to act as reference stand for immature Douglas-fir on Vancouver Island in order to calculate rainfall interception recovery for those stands.

Table B1. Long-term mean precipitation data, by season for three Vancouver Island sites: summary.

	PP_A	PP_W	PP_S	PP_{FWS}	Ratio PP_W/PP_A	Ratio PP_{FWS}/PP_A
Campbell River						
Rainfall (mm)	1344.1	985.4	299.8	1135	0.73	0.88
Snowfall (cm)	109.0	43.4	0.0			
Precipitation (mm)	1451.5	598.1	299.8			
Nanaimo						
Rainfall (mm)	1077.9	824.4	215.2	937.2	0.76	0.90
Snowfall (cm)	80.9	31.7	0.0			
Precipitation (mm)	1162.7	486.6	215.2			
Tofino						
Rainfall (mm)	3257.4	2402.8	721.3	2815.5	0.74	0.90
Snowfall (cm)	42.8	35	0.0			
Precipitation (mm)	3305.9	2449.6	721.3			

Table B2. Seasonal rainfall at Campbell River, for specific time periods.

Year	PP_A (mm)	PP_W (mm)	p_{RW}	PP_S (mm)
1995	1880.4	1464.4	0.779	416.0
1995/96	1633.3	1217.3	0.745	416.0
1996	1393.6	923.9	0.663	469.7
1997	1791.4	1152.4	0.643	639.0
1998	1800.4	1578.5	0.877	221.9
1999	1985.8	1673.5	0.843	312.3
2000	1114.0	831.5	0.746	282.5
2001	1294.8	952.8	0.736	342.0

Table B3. Determination of p' as a function of p_R using measured interception data at Gray Creek and at Campbell River, by the Direct Method (using measured interception volumes).

Plot	Stand height (m)	I_W (mm)	I_S (mm)	I_A (mm)	P'	p_{RW}
Campbell River (2000)	33	160.3	84.75	245.1	0.654	0.746
Cowichan Lake 1 (1997)	18.5	225.5	200.1	425.6	0.530	0.643
Cowichan Lake 2 (1997)	13.5	197.8	131.1	328.9	0.601	0.643
Gray Creek						
Site F	32	156.6	30.0	197.5	0.793	0.924
Site E	18	164.3	31.7	196	0.838	0.924
Site D	8.8	85.7	17.1	102.8	0.834	0.924
Rain during storms monitored for I		658.6	73.4	713.0		0.924
Total rainfall		1073.0	417.3	1490.3		0.720

Table B4. Determination of p as a function of p_R using measured interception data at Gray Creek and at Campbell River, by the Working Method (using interception ratios).

Plot	Stand height (m)	I_W (mm)	I_S (mm)	I_A (mm)	P'	p_R
Campbell River (2000)	33	19.3	30	22	0.746	0.746
Cowichan Lake 1 (1997)	18.5	18.1	29	22	0.643	0.643
Cowichan Lake 2 (1997)	13.5	15.9	19	17	0.643	0.643
Gray Creek						
Site F	32	23.8	40.9	27.7	0.771	0.924
Site E	18	24.9	43.2	27.5	0.861	0.924
Site D	8.8	14.8	23.3	16.3	0.863	0.924

Table B5. McMinn data as reported and after seasonal adjustment: reported data along with adjusted interception volumes.

Average stand height (m)	Annual values			Reported components		Adjusted components		
	PP_A (mm)	I_A (mm)	I_A (%)	PP_{fall} (mm)	PP_{summer} (mm)	Ratio p_{RW}	I_W (mm)	I_S (mm)
26.32	1733.3	421.8	24.3	1485.4	248.0	0.836	212.7	362.3
32.85	1437.5	402.5	28.0	1237.5	200.0	0.842	212.7	362.3
45.67	1426.0	399.3	28.0	1222.4	203.6	0.831	202.5	369.3
52.44	1380.0	448.5	32.5	1177.5	202.5	0.820	217.1	420.0
62.88	1347.5	542.4	40.3	1141.9	205.6	0.824	266.6	490.3
73.68	1353.3	473.7	35.0	1173.4	179.9	0.825	232.5	408.5

Table B6. McMinn data as reported and after seasonal adjustment: adjusted interception calculated by the Working Method and the Direct Method.

Average stand height (m)	Winter rainfall PP_W (mm)	Annual interception I_A (%)	Calculated seasonal interception					
			Working Method			Direct Method		
			Interception ratio p_{IW}	I_W (%)	I_S (%)	Interception ratio p'	I_W (%)	I_S (%)
26.32	1457.3	24.3	0.792	15.7	37.0	0.742	17.5	33.8
32.85	1216.4	25.0	0.797	18.1	38.5	0.748	17.5	33.8
45.67	1191.4	28.0	0.788	15.4	44.8	0.736	17.0	39.2
52.44	1138.8	32.5	0.780	18.2	49.7	0.724	19.1	46.0
62.88	1117.8	35.0	0.782	24.5	50.7	0.728	23.9	49.1
73.68	1124.2	43.5	0.783	37.0	53.0	0.729	29.6	37.4

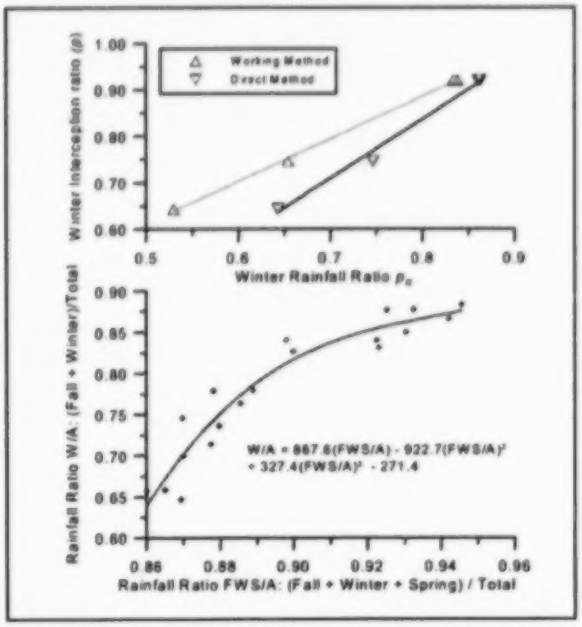
Working Method
Direct Method
Winter Interception ratio (p_i)
Winter Rainfall Ratio p_w
Rainfall Ratio W/A: (Fall + Winter)/Total
W/A = 867.6(FWS/A) - 922.7(FWS/A)² + 327.4(FWS/A)³ - 271.4
Rainfall Ratio FWS/A: (Fall + Winter + Spring) / Total

Figure B1. Relationships to convert seasonal rainfall ratio (bottom) and to derive interception ratios from rainfall ratios (top).

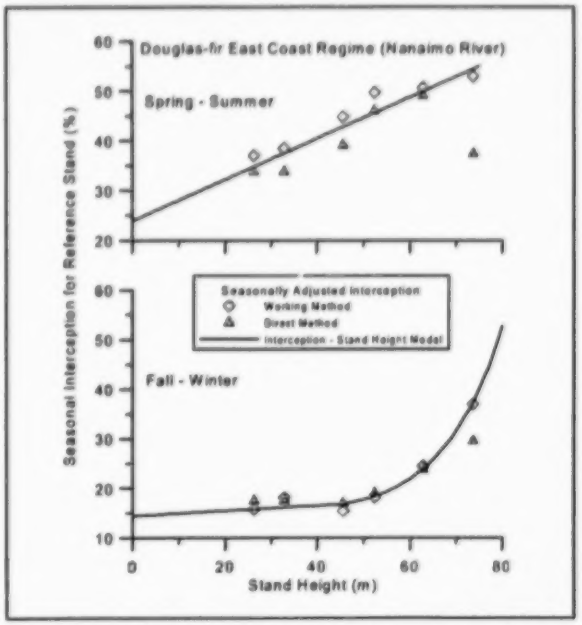

Figure B2. Relationships between interception under mature Douglas-fir and stand height for Nanaimo River (based on data from McMinn 1957).